PB-227 099

AN ECONOMIC ANALYSIS OF THE CONTROL OF SULPHUR OXIDES AIR POLLUTION

Department of Health, Education and Welfare
Washington, D. C.

December 1967

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 227 099

1967-9

Program Analysis

HUMAN INVESTMENT PROGRAMS

AN ECONOMIC ANALYSIS of the CONTROL of SULPHUR OXIDES AIR POLLUTION

December 1967

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Office of the Assistant Secretary (Planning and Evaluation)

1<

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

CONTENTS

	Page
Foreword	i
List of Tables	ii
List of Figures	iv
CHAPTER I: INTRODUCTION	I-1
CHAPTER II: OBJECTIVES AND SCOPE OF THE STUDY	
A. Objectives	II-1
B. Scope of SO_2 Pollution Problem Studied	II-2
1. Introduction	II-2
2. Abatement of SO_2 Pollution	II-3
3. Economics	II-4
4. Technical Simplifications and Assumptions	II-4
5. Limitations	II-8
CHAPTER III: METHODOLOGY FOR URBAN ABATEMENT ANALYSIS	
A. Requirements	III-1
B. Simulation	III-2
C. Model City Characteristics	III-2
D. Fuel-Use Structure	III-4
E. SO_2 Emission Inventory	III-4
F. Meteorological Model	III-5
G. Computed SO_2 Concentration	III-6
H. Available SO_2 Control Techniques	III-6
1. Fuel Substitution	III-7
2. Fuel Desulfurization	III-7
3. Stack Gas Cleaning	III-8
4. Increased Stack Height	III-9
5. Zoning and Relocation	III-10
I. Cost of SO_2 Control Techniques	III-10
CHAPTER IV: MODEL CITY ABATEMENT OBJECTIVES AND STRATEGIES	
A. Abatement Objectives	IV-1
B. Abatement Strategies	IV-2
1. Equal-Proportional Strategy	IV-3
2. Least-Cost Strategy	IV-4

	Page
CHAPTER V: COST-EFFECTIVENESS OF ABATEMENT STRATEGIES	
A. Objective 1: Reduce Total Emissions by 20, 40, 60, 80, and Maximum Percent	V-1
1. Equal-Proportional Strategy	V-1
2. Least-Cost Strategy	V-1
3. Differences in Cost of Strategies	V-1
B. Objective 2: Reduce Highest Concentration by 20, 40, 60, 80, and Maximum Percent	V-3
1. Equal-Proportional Strategy	V-3
2. Least-Cost Strategy	V-3
3. Differences in Costs of Strategies	V-3
C. Objective 3: Reduce All Concentrations to 0.050 PPM or less	V-5
1. Equal-Proportional Strategy	V-5
2. Least-Cost Strategy	V-5
D. Objective 4: Reduce Human Exposure by 20, 40, 60, 80, and Maximum Percent	V-6
1. Equal-Proportional Strategy	V-7
2. Least-Cost Strategy	V-7
3. Differences in Costs of Strategies	V-8
4. Human Exposure Weighted by Population and Concentration	V-8
5. Broader Implications of Weighting Functions	V-11
E. Effect of Time-Phasing on Costs	V-14
F. Effect of Power Plant Relocation on Costs	V-14
CHAPTER VI: CONSIDERATIONS IN REAL APPLICATIONS	VI-1
1. Decision Aids for Abatement Authorities	VI-2
2. Evaluating Emission Control Techniques	VI-3
3. Allocation of Federal Resources	VI-3
CHAPTER VII: CONCLUSIONS AND RECOMMENDATIONS	
A. Conclusions	VII-1
B. Recommendations	VII-2
APPENDICES	
Appendix A: Meteorological Diffusion Model	A-1
Appendix B: Costs Related to SO_2 Emission Control	B-1

LIST OF TABLES (cont'd.)

TABLE NUMBER	TITLE
5.10	Concentrations at Sixteen Highest Points After Reduction to 0.050 ppm or Less
5.11	Cost of Reducing Unweighted Exposure by Equal-Proportional Strategy
5.12	Cost of Reducing Unweighted Exposure by Least-Cost Strategy
5.13	Sample Weighting Functions
5.14	Sample Calculations of the Cost of Reducing Weighted Human Exposure Versus the Cost of Reducing Unweighted Human Exposure
A.1	Diffusion Model Program Listing (FORTRAN IV)
B.1	Estimated Annual Cost of Stack Cleaning
B.2.	Estimated Annual Increased Costs of a High Stack

LIST OF FIGURES

FIGURE NUMBER	TITLE
1.1	Comparison of Estimated Annual Costs of Achieving Various Abatement Objectives by Least-Cost Strategy
3.1	Flow Diagram of Model City Simulation
3.2	Geographical Layout of Model City
3.3	Average Annual Sulfur Dioxide Concentrations (ppm)--All Sources, before Abatement
3.4	Average Annual Sulfur Dioxide Concentrations (ppm)--Uptown Power Plant (Low Stack)
3.5	Average Annual Sulfur Dioxide Concentrations (ppm)--Downtown Power Plant
3.6	Average Annual Sulfur Dioxide Concentrations (ppm)--Industrial Sources
3.7	Average Annual Sulfur Dioxide Concentrations (ppm)--Commercial Sources
3.8	Average Annual Sulfur Dioxide Concentrations (ppm)--Multi-Family Sources
3.9	Average Annual Sulfur Dioxide Concentrations (ppm)--Uptown Power Plant (High Stack)
3.10	Estimated Annual Increased Fuel Costs to Uptown Power Plant for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Coal for High-Sulfur Coal
3.11	Estimated Annual Increased Fuel Costs to Downtown Power Plant for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Coal for High-Sulfur Coal
3.12	Estimated Annual Increased Fuel Costs to Industrial Sources for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Coal for High-Sulfur Coal

LIST OF FIGURES (cont'd.)

FIGURE NUMBER	TITLE
3.13	Estimated Annual Increased Fuel Costs to Commercial Sources for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Coal for High-Sulfur Coal
3.14	Estimated Annual Increased Fuel Costs to Multi-Family Sources for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Coal for High-Sulfur Coal
3.15	Estimated Annual Increased Fuel Costs to Uptown Power Plant for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Residual Oil for High-Sulfur Residual Oil
3.16	Estimated Annual Increased Fuel Costs to Industrial Sources for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Residual Oil for High-Sulfur Residual Oil
3.17	Estimated Annual Increased Fuel Costs to Commercial Sources for Reduction in SO_2 Emissions by Substitution of Low-Sulfur Residual Oil for High-Sulfur Residual Oil
3.18	Estimated Annual Increased Operating Costs to Power Plants for Reducing SO_2 Emissions by Installation of Stack Gas Cleaning Equipment
3.19	Average Annual Sulfur Dioxide Concentrations (ppm)-- All Sources (Power Plant Out of Town)
5.1	Average Annual Sulfur Dioxide Concentrations (ppm)-- All Sources, Maximum Reduction
5.2	Comparison of Estimated Annual Costs of Reducing Emissions--Equal-Proportional and Least-Cost Strategies
5.3	Average Annual Sulfur Dioxide Concentrations (ppm)-- All Sources, 60% EP Reduction
5.4	Average Annual Sulfur Dioxide Concentrations (ppm)-- All Sources, 60% LC Reduction

6<

LIST OF FIGURES (cont'd.)

FIGURE NUMBER	TITLE
5.5	Comparison of Estimated Annual Costs of Reducing Highest Concentrations--Equal-Proportional and Least-Cost Strategies
5.6	Average Annual Sulfur Dioxide Concentrations (ppm)--All Sources, LC Reduction of All Concentrations to Less Than 0.050 ppm
5.7	Comparison of Estimated Annual Costs of Reducing Unweighted Human Exposure--Equal-Proportional and Least-Cost Strategies
A.1	Plume from Single Source
A.2	Diffusion Model Program Logic
B.1	Incremental Cost of Coal to Power Plants and Industrial Consumers Vs. Percent Reduction in Sulfur Content
B.2	Incremental Cost of Coal to Commercial and Multi-Family Consumers Vs. Percent Reduction in Sulfur Content
B.3	Incremental Cost of Residual Oil to All Consumers Vs. Percent Reduction in Sulfur Content
B.4	Range of Incremental Costs of Power Plant Coal Vs. Sulfur Content
B.5	Incremental Costs of Desulfurized Coal
B.6	Range of Incremental Costs of Power Plant Residual Oil Vs. Sulfur Content
B.7	Incremental Cost of Desulfurized Residual Oil

7<

FOREWORD

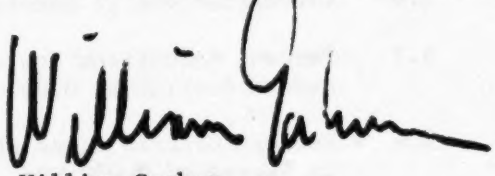
Program analysis in the Department of HEW is still in an exploratory stage. Since the spring of 1966, when Secretary Gardner asked that my Office establish program analysis groups to analyze the Department's programs, we have found that different programs demand different approaches. Some can be structured so that they are amenable to cost-effectiveness analysis; with others, the choices to be made are more clearly illuminated by estimating the costs and benefits of the programs in question; in still others the data are so primitive that no formal structured analysis is at all justified. The Air Pollution Program Analysis Group opted for developing a pilot model which could eventually provide a framework for evaluating alternative air pollution abatement programs.

The model demonstrates three things: (1) the type of information required to select a preferred regional abatement policy; (2) the types of constraints to be overcome before actually activating the techniques; and (3) the amount of cost differential resulting from the application of various public policy alternatives to the problem of reducing pollution.

The model will eventually be useful in determining: (1) allocational priorities for preferred abatement objectives; (2) the research and data needs of the National Center for Air Pollution Control; and (3) "problem shed" areas in the Nation.

The Air Pollution Program Analysis Group was under the chairmanship of Dr. B. J. Steigerwald (NCAPC).

The Study's meterological dispersion model was constructed by J. Farmer and J. W. Richhart of NCAPC in Cincinnati, Ohio. Consultation with D. B. Turner was also helpful. Much of the detailed work of the Study was carried out by the Management Services Division of Ernst & Ernst, Washington, D. C.



William Gorham
Assistant Secretary for
Planning and Evaluation
October 1967

LIST OF TABLES

TABLE NUMBER	TITLE
3.1	Principal Characteristics of Model City
3.2	BTU Requirements of Model City
3.3	SO_2 Emission Inventory
3.4	Availability of Techniques for SO_2 Control
3.5	Summary of Maximum Reduction in Emissions and Costs Related Thereto
5.1	Cost of Reducing Emissions by Equal-Proportional Strategy
5.2	Cost of Reducing Emissions by Least-Cost Strategy
5.3	Contributions to Concentration at Coordinates H-517.5 and V-712-6
5.4	Reduction of Highest Concentration by Equal-Proportional Strategy
5.5	Cost of Reducing Highest Concentration by Least-Cost Strategy
5.6	Concentrations in Excess of 0.050 ppm
5.7	Percent Reductions Necessary to Reduce Concentrations Before Control to 0.050 ppm or less
5.8	Percent Contributions of All Sources to Concentrations in Excess of 0.050 ppm
5.9	Cost of Reducing Concentrations to 0.050 ppm or less--Least-Cost Strategy

9<

I. INTRODUCTION

The initial charge to the Health Program Analysis Group--Air Pollution was to study all aspects of the sources and control of air pollution. In that charge, emphasis was to be placed on determining the relative effectiveness of the various pollution control techniques and upon developing optimum control strategies. The factors contributing to air pollution vary widely between cities. Therefore, universally optimum control strategies and control techniques are not likely to exist, even for a single pollutant. Because of limited time and resources, the Group decided to concentrate on developing a basic methodology for cost-effectiveness analysis of air pollution abatement strategies, using the sulfur oxides (specifically SO_2 derived from combustion) for demonstration. The study of other pollutants, such as particulate matter, CO, NO, and photochemical smog, is therefore deferred, but the methods of this study may be applied equally well to their analysis.

The analytical approach developed in the course of this study is a form of simulation, relying heavily upon a computerized meteorological model to translate pollutant emission data into ground-level concentration predictions. With this meteorological model, it is possible to simulate the improvement in air quality resulting from various combinations of control techniques. Given such simulated improvement and information on the costs of the various control techniques, an optimum (or least-cost) strategy can then be calculated for effecting any stated air quality objective.

For purposes of demonstration, this simulation technique was applied to a hypothetical model city that is assumed to be realistic in regard to SO_2 emissions. Construction of the model city required specification of:

- Geographical location and size of its power plants, industrial sector, commercial sector, multi-family residential sector, and single-family residential sector;
- Fuels used and resulting SO_2 emissions from each power plant and sector;
- Costs of the various emission abatement techniques available to each power plant and sector;
- Population densities in each sector; and
- Meteorological data, such as wind velocities and directions.

These same types of information will be required for the application of the simulation technique to any real city.

There are many possible pollution abatement objectives that might be of interest in a real city. The following four objectives, which are both interesting in themselves and representative of the range of possibilities, were investigated for the model city:

1. Reduction of total SO_2 emissions in the city by 20, 40, 60, 80, and maximum percent;
2. Reduction of the average annual SO_2 concentration in the most polluted portion of the city by 20, 40, 60, 80, and maximum percent;

3. Reduction of all average annual SO_2 concentrations in the city to 0.050 parts per million or less, as a first step toward an ultimate goal (e.g., 0.015 ppm); and
4. Reduction of total annual human exposure to SO_2 in the city by 20, 40, 60, 80, and maximum percent.

Note that analysis of Objective 1 does not require use of the meteorological model because it is concerned only with the sources of pollutants rather than with the effect of those pollution sources on air quality.

For each pollution abatement objective, two control strategies were considered. The first, called the Equal-Proportional (EP) strategy, reduces the SO_2 emissions from each source in the city by the same percentage, that percentage being the smallest required to meet the stated objective. Under this strategy, the meteorological model is used to determine the required percentage reduction, and then the cost of that "across-the-board" reduction is computed. The second strategy, called the Least-Cost (LC) strategy, employs that combination of emission control techniques (in one or more sectors of the city) which accomplishes the stated objective at minimum total cost. Under this strategy, simulated meteorological results are used simultaneously with emission control technique unit costs to determine the least-cost control combination.

It must be emphasized that the numerical results derived in this study <u>apply to the hypothetical model city only</u>. Still they

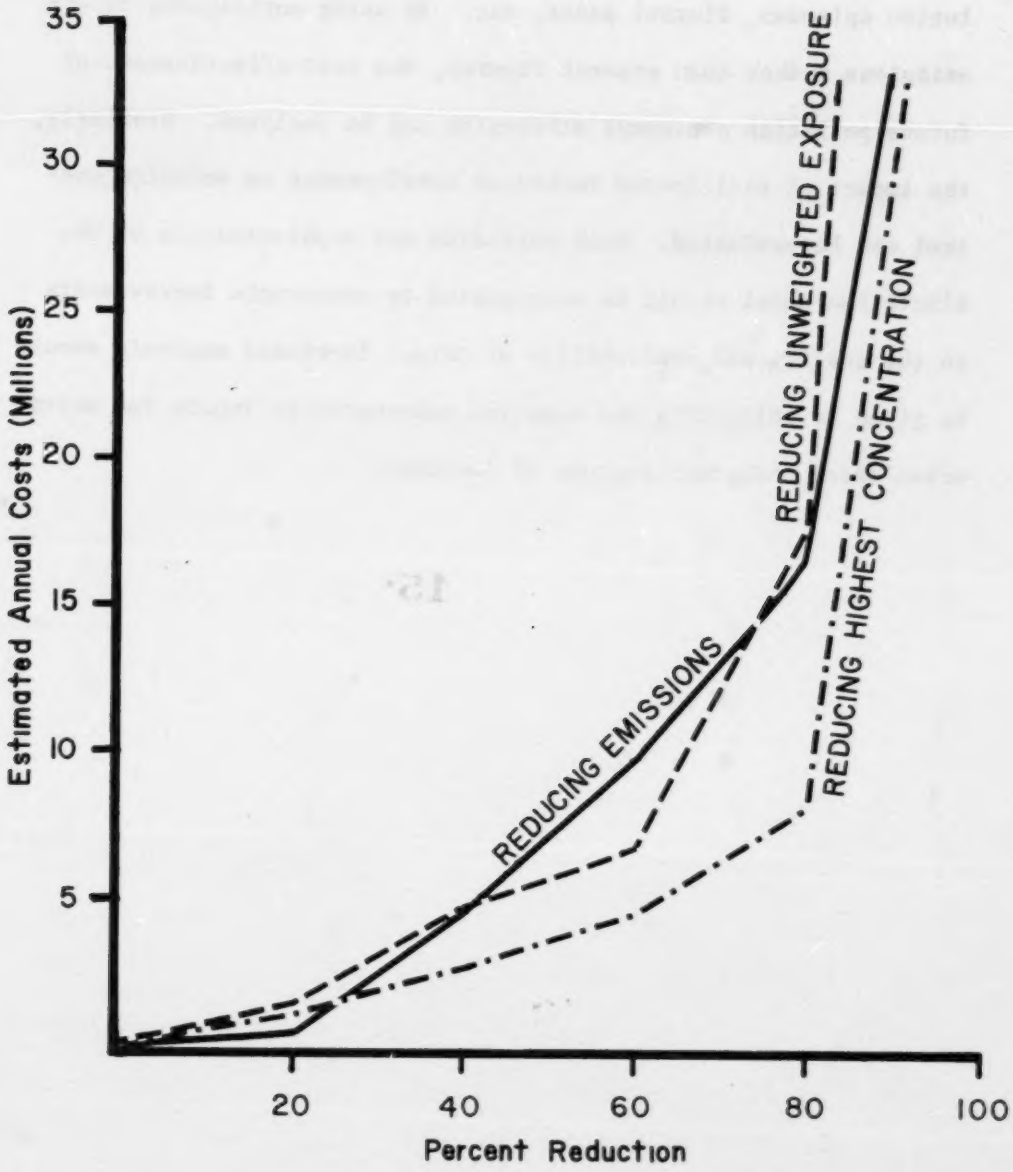
may be used to support several limited qualitative results. First, the cost computations in Chapter V show that, for each of the four objectives, the administratively appealing EP strategy may be far more expensive than the economically optimum LC strategy. For example, to reduce the highest average annual concentration in the model city by 60% (Objective 2), the EP strategy costs almost three times as much as the LC strategy ($12,743,000 versus $4,520,000).

A second interesting result for the model city, which may hold to a greater or lesser extent for real cities, concerns the comparative cost of achieving different abatement objectives. Figure 1.1 shows the minimum cost (i.e., by LC strategy) of achieving Objectives 1, 2, and 4. It is seen that, at each level, other than maximum reduction, there are wide cost differences in achieving the objectives. For example, a 60% concentration reduction in the area of highest concentration costs $4,520,000, a 60% reduction in emissions costs $8,967,000, and a 60% reduction in human exposure costs $12,743,000. Thus, on a least-cost basis, the total cost of a pollution abatement program may depend heavily upon its defined objectives, or equivalently, upon its definition of "abatement."

In conclusion, the combination of meteorological simulation and economic analysis provides a powerful and flexible analytical method for evaluating the cost-effectiveness of pollution abatement alternatives in any specific area. The types of informational output demonstrated in this study represent only a first step in the development of sophisticated simulation. A general simulation

FIGURE 1.1

COMPARISON OF ESTIMATED ANNUAL COSTS OF ACHIEVING VARIOUS ABATEMENT OBJECTIVES BY LEAST-COST STRATEGY



model which is equally applicable to all pollutant types, or which can consider many pollutants simultaneously, should be developed from the work begun here. Through changes in the meteorological model, emphasis can be shifted from average annual effects to pollution episodes, diurnal peaks, etc. By using anticipated future emissions rather than present figures, the cost-effectiveness of future pollution abatement strategies can be analyzed. Similarly, the impact of anticipated technical developments in emission control can be evaluated. Such expansion and sophistication of the simulation model should be accompanied by comparable improvements in the quality and availability of data. Increased emphasis should be given to collecting the required informational inputs for major urban areas and other regions of interest.

II. OBJECTIVES AND SCOPE OF STUDY

This chapter sets forth the objectives and scope of the study and the limitations imposed by considerations of time, resources, and available information.

A. OBJECTIVES

This program analysis of the abatement of sulfur oxide pollution has two primary objectives:

- To demonstrate the value of systems-analysis and simulation for assessing the costs of various clean air goals, and the cost-effectiveness of alternative pollution abatement strategies.

- To provide officials charged with the responsibility for air pollution control with an indication of information needs in pollution abatement analysis. These needs can suggest directions for DHEW research policy.

Each of these objectives is multifaceted and is directly related to the structure of the study itself. On both accounts, the objectives require further elucidation.

1. The first objective recognizes two points. First, the emission of SO_2 should be controlled with the minimum of public and private expenditure consonant with the level of control desired. Second, because of differences in urban meteorology, distribution and levels of emissions, and the availability of alternative techniques for emission control, the abatement of SO_2 pollution requires analysis by each metropolitan area individually. An analytical procedure

encompassing these two points recognizes that there are alternative abatement strategies available to each urban area affected by SO_2, with different costs attached to each strategy.

2. The second major objective of the study has three components. First, it will point out to those responsible for achieving air pollution abatement the need for the best quantitative techniques available for decision-making. Second, the demonstration study will serve to reveal the complexities inherent in pollution abatement analysis, and the scope of the effort required to apply analytical techniques to real urban areas. Third, this demonstration will thus point out information gaps which will require further research before real applications can begin.

B. SCOPE OF SO_2 POLLUTION PROBLEM STUDIED

1. Introduction

Air pollution is a complex phenomenon which has an important impact on the economic, social, political, technological, and public health areas. It would not be possible, in analyzing a specific air pollution situation within the time available, to consider quantitatively the impact of pollution or abatement in all these areas, and therefore some focusing is necessary. Accordingly, this analysis has been channeled in several important ways:

- The study is limited to abatement of that portion of SO_2 pollution which derives from combustion of fossil fuels; other sources of SO_2 are not considered.

- The study focuses principally on the economic aspects of pollution abatement.

- Selected technological simplifications have been made within the sulfur pollution area.

These are discussed in more detail in this section to provide an orientation to the adequacy and the limitations of this analysis and to assist in making judgments on the value of the recommendations and conclusions.

2. Abatement of SO_2 Pollution

An analysis of air pollution begins very early to break down into several separate studies of significant air pollution problem areas; included among these are: sulfur (combustion and industrial processes), photochemical smog (transportation), particulate matter (combustion and industrial processes), odor (industrial processes, refuse disposal), and fuel additives and carbon monoxide (transportation).

Although this report considers only SO_2 pollution, it is recognized that some lesser beneficent effects on levels of other pollutants may result from certain methods of SO_2 control. For example, when gas is substituted for coal or oil, there will also be fewer particulates and less NO_x emitted. To the extent that SO_x may contribute to lowered visibility in photochemical smog, there may be some further small benefit from controlling SO_x alone. These considerations, however, should make the report more, rather than less, conservative, and should not detract from the realism and meaningfulness of the cost-effectiveness and alternative-solution analyses of the sulfur control programs.

3. Economics

Although this analysis is concerned primarily with the economics of air pollution abatement, it is recognized that abatement regulations and policies can have significant consequences which are not of an economic nature. In the sulfur area, these include effects on foreign policy caused by sulfur restrictions on imported residual oil; national defense needs; considerations of long-range natural resource conservation in developing fuel policies; severe social and economic disruptions from forced changes in normally stable fuel use patterns; political implications; and interrelationships among local, State, and Federal governments. The existence of these noneconomic factors is recognized and they have influenced, to a certain degree considerations of the practicality of alternative solutions. It has not been possible to include them in the quantitative economic analyses. It is generally recognized at policy-making levels that economics is only one factor in considering SO_2 control policies; our inability to include social and political parameters in this study does not detract from its validity.

4. Technical Simplifications and Assumptions

Even after narrowing the analysis to the economics of SO_2 control, additional simplifications and assumptions are required before a meaningful study can be made with the time and resources available. The most important of these simplifications are listed below and discussed briefly:

(a) Sources

Approximately 85 percent of SO_2 emitted to the atmosphere comes from the combustion of fuels; smelters, sulfuric acid plants,

various industrial processes, incinerators, and burning coal refuse piles account for the remaining portion. In major urban areas, over 90 percent of the SO_2 in the atmosphere is emitted by combustion sources. Since control schemes for smelters, acid plants, etc., are different from those for combustion sources, the analysis is greatly simplified with little loss of value by ignoring noncumbustion sources at this time.

(b) Interactions with other pollutants

It is impossible to distinguish completely the effects of SO_2 from those of other pollutants. Particulate matter is of special interest since it has been implicated in potentiating or increasing appreciably some of the health and possibly the materials-damaging effects of SO_2. The suggestion that SO_2 effects could be negated simply and economically by requiring a high degree of control for particulates has not been included as an alternative solution, for the following reasons:

(1) Some SO_2 effects have not been linked to particulates;

(2) the background level of natural particulates, including fogs, is often high enough to limit attempts to reduce particulates to very low levels; and

(3) SO_2 undergoes changes in the atmosphere to produce significant particulate matter such as sulfate and sulfuric acid.

It is probable that even partial control of particulates will reduce SO_2 effects, but there is not enough information available at this time to allow an economic analysis of partial particulate

control as a way to reduce damage from SO_2.

The terms sulfur dioxide and sulfur oxides (including SO_3, particulate sulfate, and sulfuric acid aerosols) are used interchangeably in this report. Sulfur dioxide is continually being converted to sulfate and acid in the atmosphere and it is impossible to make separate damage estimates for each of the forms of sulfur oxides. Also, the only known way to reduce concentrations of particulate sulfur compounds in the atmosphere is to reduce SO_2 emissions.

Sulfur dioxide does become involved in photochemical smog reactions, probably causing reduced visibility. However, SO_2 is not considered a major element in photochemical smog production, smog effects, or smog control and therefore smog interactions were not included in the analysis.

(c) Time-concentration relationships

The amount of SO_2 in the atmosphere varies continuously and statements of concentrations must be related to the averaging period to be meaningful; thus a city might have an annual mean concentration of 0.1 parts per million, a peak day of 0.4 ppm, a peak hour of 0.7 ppm, and an instantaneous peak value at one point of 2.8 ppm. The different time-concentration values are not mutually independent but are connected by meteorology and source strength considerations. Therefore, control to selected annual average levels will generally guarantee control of short-term peaks. The opposite is not true, however, and "peak-lopping" (i.e., by substituting low-sulfur fuel during several air stagnation days) will probably not influence annual average concentrations by any large amount.

Although some effects predominate during the short-term, high-concentration periods, many effects relate to long-term average levels.

Since published SO_2 air quality criteria [1] stress long-term average levels, it seems most valuable to utilize in this study the long-term average SO_2 concentration as the indicator of pollution levels and control effectiveness. Therefore, the analysis does not include cost studies on "peak-lopping" techniques as temporary measures for controlling short-term, high-concentrations or any cost-effectiveness analysis for air pollution episode situations. These are significant considerations, however, and should be included in actual urban pollution analysis.

(d) Intercity transport

In this study the metropolitan area will be the principal geographical area of concern. It is recognized that large elevated point sources that may not contribute significantly to ground-level concentrations in the original urban complex will add either to the rural background level or possibly to the SO_2 level in distant cities. Conversely, elevated rural sources can intensify the urban problem.

(e) Model city

A model city has been structured in Chapter III for this analysis which contains most types of SO_2 combustion sources; their variation and distribution have been greatly simplified to facilitate

---

[1] Air Quality Criteria for Sulfur Oxides, U.S. Department of HEW, Public Health Service, Bureau of Disease Prevention and Environmental Control, Washington, D.C., March, 1967.

computations. It has been assumed that all sources emit SO_2 at a uniform rate throughout each day and season of the year; that the emission rate per square mile is constant for each selected land-use area (commercial, industrial, multi-family) and that each area is used for only one purpose (e.g., no homes in the industrial sector).

(f) Control options

The primary control techniques considered for SO_2 emitted from combustion sources were fuel modification and substitution, stack gas cleaning, increased stack height, and relocation of major sources. However, the complete spectrum of options within each control technique could not be allowed. For example, a power plant using 50% coal and 50% residual oil could independently modify the sulfur content of each but could not alter the proportion of energy produced by coal or oil. It was assumed that reasons other than air pollution determined the original mix and would dominate the final picture. Other constraints or simplifications were applied to other control possibilities. These are discussed in detail under "Available SO_2 Control Techniques" in Chapter III.

C. LIMITATIONS

In addition to the constraints referred to above--which were willfully imposed in the interest of keeping this "pilot study" within bounds the following limitations apply throughout this study:

1. More data must be gathered and analyzed before confident statements with regard to the economic and social benefits and costs of SO_2 abatement alternatives can be supported.

2. The severe time limitations imposed on this study have not allowed use of all available information on SO_2 pollution and its control, and the pollution situation studied has been simplified significantly so that the major objectives of the analysis could be achieved.

3. Local variations in SO_2 source strength and distribution, land-use patterns, meteorology, future growth, etc., will require slightly different models for each area or region and will probably result in significantly different solutions for each locality.

4. It has not been possible to examine the research programs being pursued and their probabilities for success. It is not a purpose of this study to assess the payoffs of various research time-phasings and tradeoffs.

5. The method used in comparing alternative strategies for achieving an objective was a simple manual procedure; obviously, the level of sophistication would have been increased significantly if a computer were employed to compare several thousand strategies.

6. Furthermore, time has not permitted examination of the economic effects, administrative difficulties, and probable success of the Federal programs designed to hasten the abatement of SO_2 in the private sector.

III. METHODOLOGY FOR URBAN ABATEMENT ANALYSIS

This chapter presents the methodology developed to demonstrate the simulation approach to assessing the costs of various clean air goals and the cost and effectiveness of alternative pollution abatement strategies.

A. REQUIREMENTS

The development of a methodology for analysis of air pollution abatement has been guided by several key requirements:

- The method must have application to a wide range of urban environments with different pollution sources, fuel use and cost structures, meteorology, and different abatement objectives.

- The method must be capable of generalization to accommodate abatement analysis of many different pollutants--not only sulfur oxide.

- The method must not only become increasingly more powerful as research provides more and better data concerning air pollution, but also be useful immediately with present data.

The method must be useful at the Federal, State, and local levels, not only for examining the cost-effectiveness relationships implied by a given abatement policy, but also for judging the efficacy of competing incentives for abatement, and for indicating productive avenues of research in pollution control.

B. SIMULATION

The analytical technique which best satisfies the above requirements is a computer-assisted simulation of the urban area of interest which can rapidly calculate the effect of local meteorology on pollutant concentrations ascribable to identified sources of emissions and can incorporate the cost of incremental control.

To demonstrate the power of simulation in analysis of pollution abatement, the method has been applied to a "model city," which, although fictional, has realistic size, population, economic structure, fuel use, meteorology, and SO_2 pollution levels, and a set of feasible SO_2 control techniques at the time of interest (1970).

The essential elements of the model city simulation are related in the flow diagram given in figure 3.1, which constitutes the analytical model upon which this study is based.

C. MODEL CITY CHARACTERISTICS

The stylized geographical layout of the model city is depicted in figure 3.2. Note that the city has both an uptown and a downtown electrical power plant, an industrial sector, and a commercial sector surrounded by multi-family dwellings and single-family dwellings. The grid coordinate system imposed on the layout is numbered to be compatible with a computerized meteorological diffusion program already written (see F below). The grid system is used to locate both SO_2 sources and the receptor points at which SO_2 concentrations on the ground are computed. In addition to the power plants, the other sources

FIGURE 3.1

FLOW DIAGRAM OF MODEL CITY SIMULATION

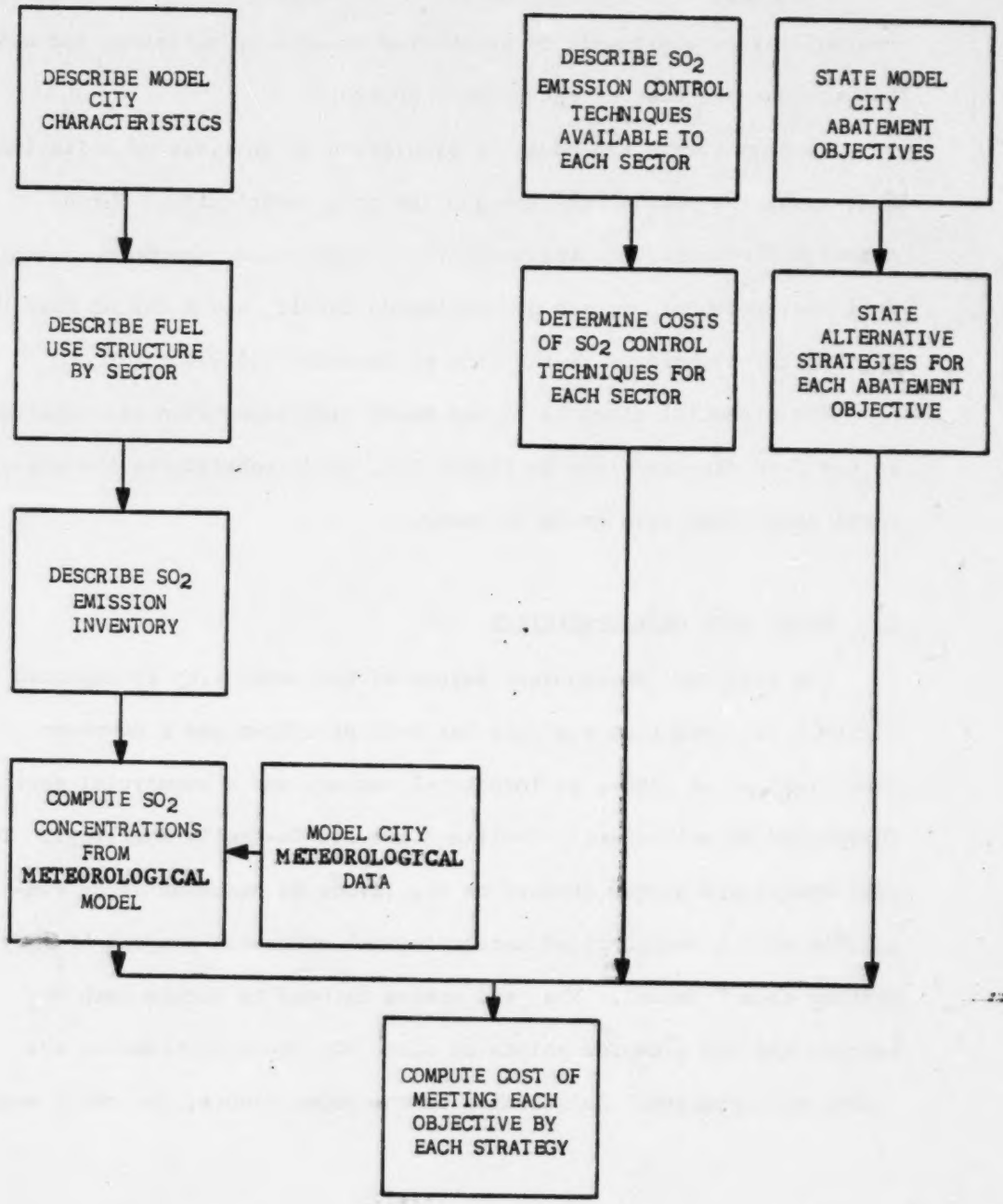

DESCRIBE MODEL CITY CHARACTERISTICS
DESCRIBE FUEL USE STRUCTURE BY SECTOR
DESCRIBE SO_2 EMISSION INVENTORY
COMPUTE SO_2 CONCENTRATIONS FROM METEOROLOGICAL MODEL
MODEL CITY METEOROLOGICAL DATA
DESCRIBE SO_2 EMISSION CONTROL TECHNIQUES AVAILABLE TO EACH SECTOR
DETERMINE COSTS OF SO_2 CONTROL TECHNIQUES FOR EACH SECTOR
STATE MODEL CITY ABATEMENT OBJECTIVES
STATE ALTERNATIVE STRATEGIES FOR EACH ABATEMENT OBJECTIVE
COMPUTE COST OF MEETING EACH OBJECTIVE BY EACH STRATEGY

TABLE 3.1

PRINCIPAL CHARACTERISTICS OF MODEL CITY

Total population	2,000,000
Employment:	
Industrial	440,000
Commercial	360,000
Number of entities/unit:	
Industrial	8,000
Commercial	45,000
Single-family	457,000
Multi-family	160,000
Number of people per:	
Single-family unit	3.5
Multi-family unit	2.5
Number of employees per:	
Industrial entity	55
Commercial entity	8
Number of units/entities per square mile:*	
Single-family	3,300
Multi-family	13,000
Industrial	275
Commercial	11,250

* Square mile as used herein equals 25,000,000 square feet.

TABLE 3.1 (cont'd.)

PRINCIPAL CHARACTERISTICS OF MODEL CITY

Size:	
Single-family area	119 square miles
Multi-family area	12 square miles
Industrial area	30 square miles
Commercial area	4 square miles
Power Plants:	
Uptown plant in northwest area operates 24 hours/day at heat rate of 9,000 BTU/kwh. Downtown plant in commercial area operates during daylight hours at heat rate of 15,000 BTU/kwh.	
Stack Heights:	
Power plants	
Uptown (200 meters for high stack)	100 meters (330 feet)
Downtown	50 meters (165 feet)
Industrial (all same)	30 meters (99 feet)
Commercial (all same)	40 meters (132 feet)
Multi-family (all same)	15 meters (49.5 feet)
Exposure Densities (Average number of people per square mile per day):*	
Single-family	11,600
Multi-family	24,300
Commercial	44,600
Industrial	4,900

* Average length of work day is assumed to be eight hours. In addition, daily migration from the single- and multi-family sectors to the commercial sector has been assumed to involve 350,000 people with an average stay of four hours.

of SO_2 emission are indicated by "o" for a total of fifteen point sources. Emissions from the industrial, commercial, and multi-family sectors are divided equally between the point sources within each sector.

Table 3.1 gives all of the quantified characteristics of the model city required both for computer inputs and for the subsequent cost-effectiveness analysis. The total population is about one percent of the projected population of the United States in 1970. The other characteristics of table 3.1 are compatible with this population and are assumed to be realistic for a city on the East Coast, although no attempt was made to model an actual city.

TABLE 3.2
BTU REQUIREMENTS OF MODEL CITY[1/]

Requirements by Sector in BTU $X10^{12}$	FUEL			
	Coal	Oil	Distillate Oil & Natural Gas	Total
power plants	90.6[2/]	49.4[4/]	0	140.0
industrial	21.0[2/]	29.0[4/]	73.0	123.0
commercial	3.0[3/]	12.0[4/]	12.0	27.0
multi-family	1.0[3/]	0	16.0	17.0
single-family	0	0	56.0	56.0
TOTAL	115.6	90.4	157.0	363.0

1/ Data represent projected national fuel-use structure for 1970, abstracted from Resources in America's Future, Resources for the Future, Inc., Johns Hopkins Press, 1963.

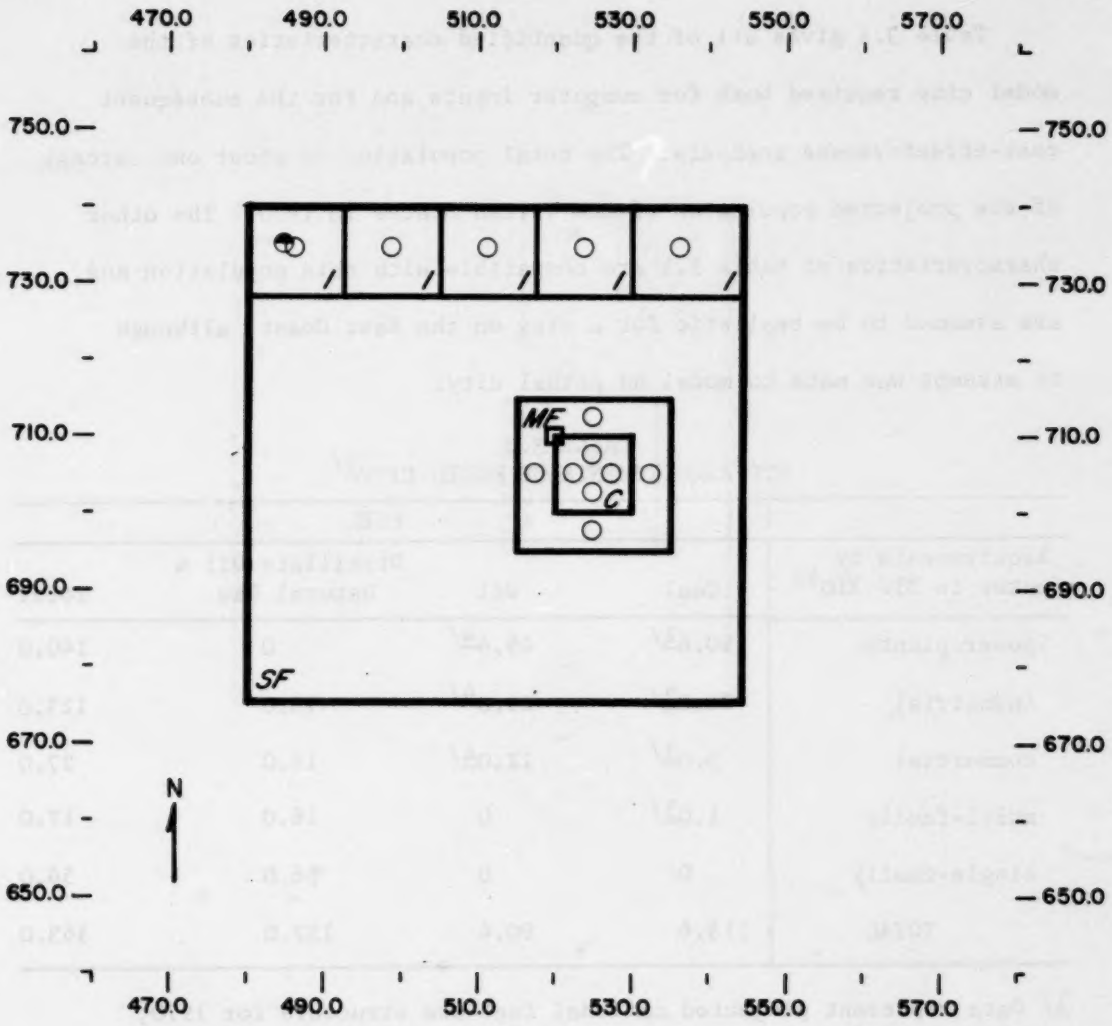
2/ 2.5 percent sulfur coal with a BTU rating of 24 million BTU/ton is assumed.

3/ 3.0 percent sulfur coal with a BTU rating of 24 million BTU/ton is assumed.

4/ 2.5 percent residual oil with a BTU rating of 6.3 million BTU/barrel is assumed.

FIGURE 3.2

GEOGRAPHICAL LAYOUT OF MODEL CITY



D. FUEL-USE STRUCTURE

Table 3.2 gives the BTU (British Thermal Unit) combustion requirements for each economic sector and the portion of these requirements satisfied by the fuels indicated before SO_2 abatement. For the reasons discussed in subsection B.4(a) of Chapter II, SO_2 emissions within the city are assumed to result only from combustion of fossil fuels. Other sources of SO_2 are not considered. Use of coal for space heating of single-family dwellings is considered to be negligible on the East Coast by 1970 and is therefore ignored. It is recognized that the use of coal for space heating in homes may produce an SO_2 problem in the immediate area, but this study is restricted to an analysis of abatement alternatives for only major sources of urban SO_2 pollution. Also, distillate oil and natural gas, which are not usually significant sources of SO_2 pollution, are assumed to have no SO_2 emissions. They are included in table 3.2 to reflect a realistic urban fuel-use structure. For simplicity, it is assumed that consumers cannot change from one kind of fuel to another, e.g., from coal to natural gas, or in the case of an existing fuel mix, change the proportion of BTU's produced by each fuel.

E. SO_2 EMISSION INVENTORY

From the BTU requirements satisfied by coal and residual oil and assumed sulfur contents specified in table 3.2, it is possible to compute the annual tonnage and the mean number of grams/second of SO_2 emitted by each sector. These emissions are given in table 3.3.

TABLE 3.3

SO_2 EMISSION INVENTORY

SOURCE	TONS PER YEAR			SO_2 EMISSIONS GMS/SEC
	COAL	RESIDUAL OIL	TOTAL	
Power plants:				
Uptown	97,700	64,700	162,400	4,660
Downtown	81,500	-0-	81,500	2,340
TOTAL FROM POWER PLANTS	179,200	65,700	243,900	7,000
Industrial	41,500	38,000	79,500	2,280
Commercial	7,100	15,700	22,800	655
Multi-family	2,400	-0-	2,400	70
TOTAL FROM OTHER SOURCES	51,000	53,700	104,700	3,005
TOTAL	230,000	118,400	348,600	10,005

F. METEOROLOGICAL MODEL

At the heart of the simulation method demonstrated in Chapter V is a computerized meteorological ("met") model developed by personnel of the National Center for Air Pollution Control, U.S.P.H.S., Cincinnati, Ohio. The met program calculates average (mean) annual ground-level pollutant concentration (in parts per million, ppm) at one or more receptor points from a single point source based upon a Gaussian diffusion formula. Required inputs to the computer are grid coordinates of the pollutant source, grid coordinates of the receptor points, effective stack height of the source (1.65 x actual stack height in meters), emission rate of pollutant in gms/sec, and wind speed and direction data appropriate to the studied area. The simplified met program was written for the IBM 1130 digital computer in FORTRAN IV language. Wind data from a large metropolitan area were used for the model-city simulation, with computer concentrations taken as average annual concentrations. (Further details of the met model are included in Appendix A, including a FORTRAN IV listing of the program.

No claim is made that the present met model provides valid measures of pollutant concentrations under all circumstances. Validation of the model for real applications will require much actual comparison of computer concentrations with observed concentrations under a variety of conditions. The ultimate usefulness of the simulation method for analyzing actual abatement cost-effectiveness is obviously dependent on met model validation and improvement which is currently being carried on elsewhere. But this question need not detract from the present demonstration of the value of simulation as an analytical tool in air pollution control.

G. COMPUTED SO_2 CONCENTRATIONS

From the emission inventory for the model city given in Section E above, computed SO_2 ground concentrations were furnished by the IBM 1130 computer employing the met model. Figure 3.3 shows the composite isopleths (contours of equal concentrations) depicting the pollution problem of the model city before abatement. Note that only the southwest corner of the city has average annual concentrations less than 0.015 ppm, the concentration at which increased hospital admissions due to SO_2-induced respiratory ailments have been observed.* The highest concentration is 0.316 ppm at grid coordinates H-517.5 and V-712.5 (H = horizontal, V = vertical).

Figures 3.4, 3.5, 3.6, 3.7, and 3.8 show the concentrations due to the uptown power plant, the downtown power plant, the industrial sector, the commercial sector, and the multi-family sector, respectively. The concentration at any point is simply the sum of the concentrations contributed to that point by the fifteen point sources. Also, the concentration contributed by an emission source to a point varies directly as the emission rate of the source. The isopleths in the figures were drawn from concentrations calculated at 44 receptor points throughout the model city.

H. AVAILABLE SO_2 CONTROL TECHNIQUES

Most of the currently available techniques for controlling SO_2 from combustion sources were considered in this study. However, it was not possible to allow all options within each emitting sector. Neither was

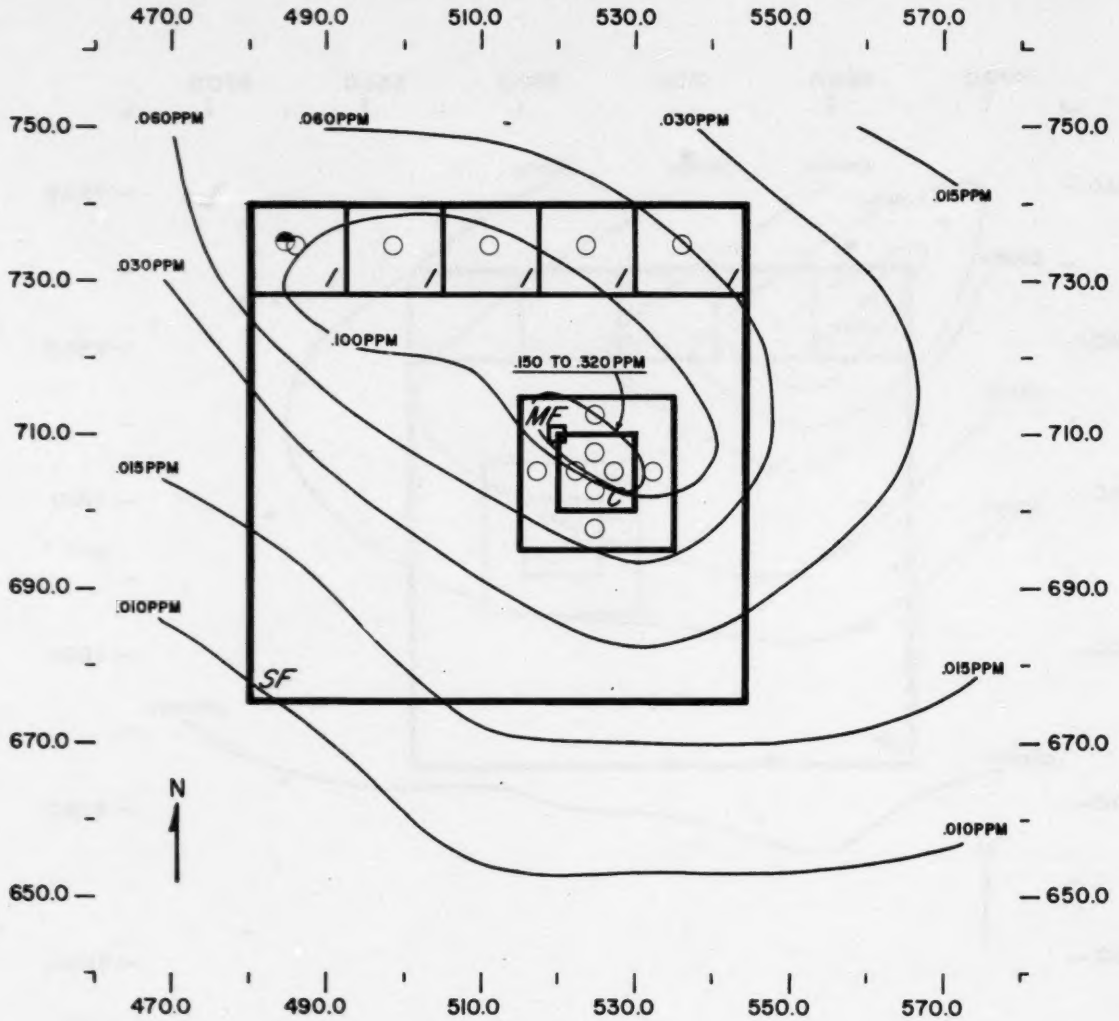
---

* Air Quality Criteria for Sulfur Oxides, op. cit., p. liii.

FIGURE 3.3

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

ALL SOURCES, BEFORE ABATEMENT



— EQUALS 1 MILE

◓ UPTOWN POWER PLANT WITH 100 METER STACK

□ DOWNTOWN POWER PLANT

○ ALL OTHER SOURCES

/ INDUSTRIAL

MF MULTI-FAMILY

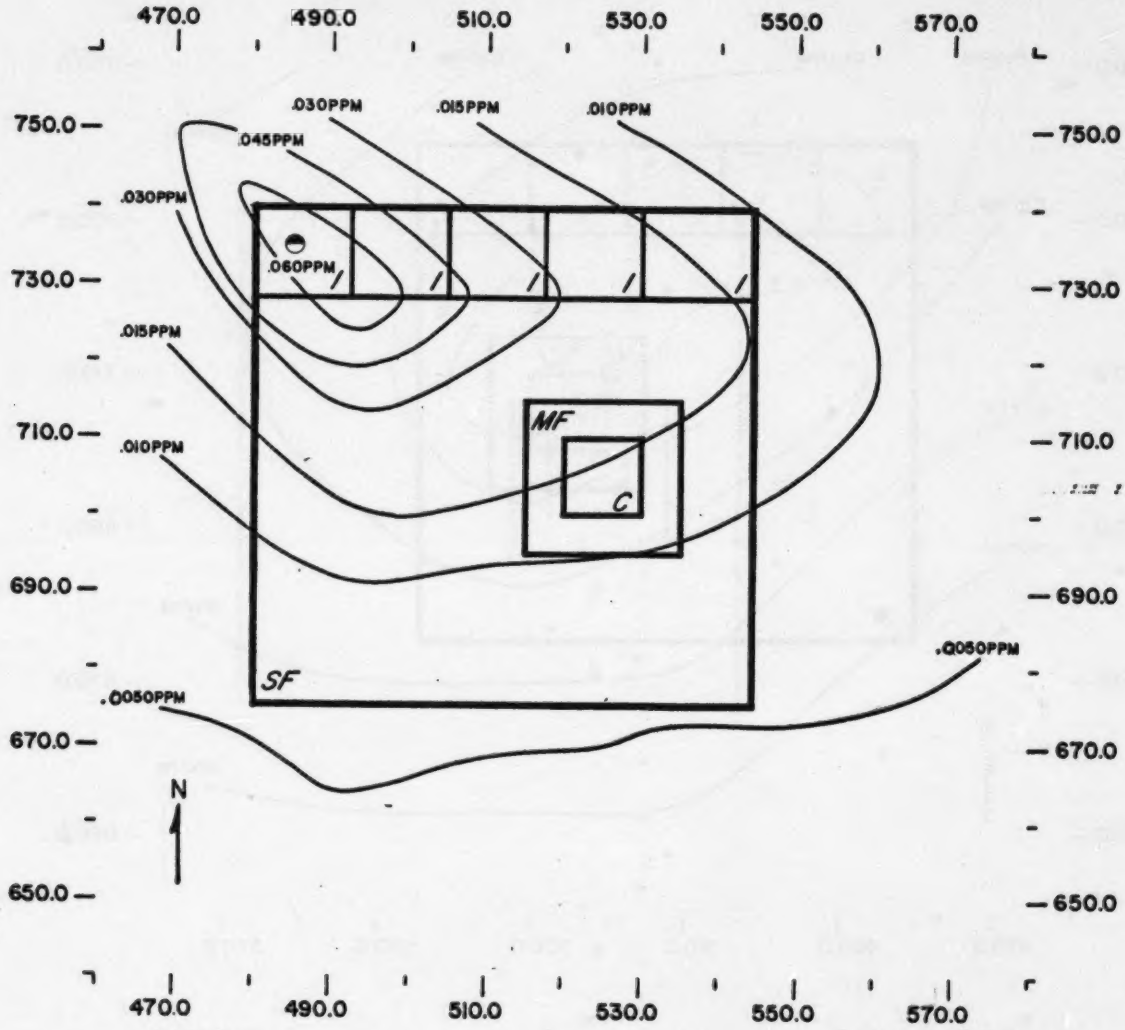
C COMMERCIAL

SF SINGLE FAMILY

FIGURE 3.4

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

UPTOWN POWER PLANT (LOW STACK)



EQUALS 1 MILE

UPTOWN POWER PLANT WITH 100 METER STACK

/ INDUSTRIAL

MF MULTI-FAMILY

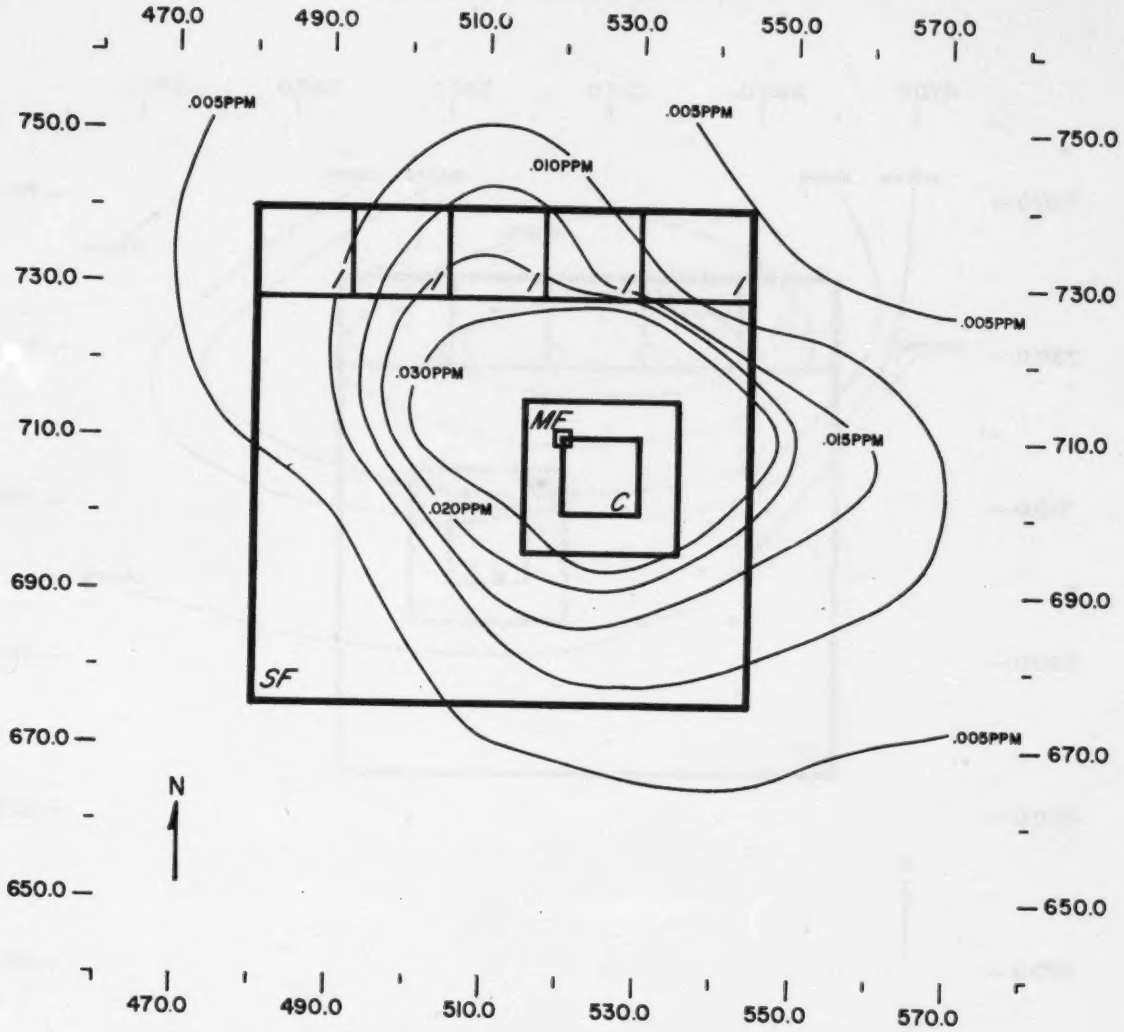
C COMMERCIAL

SF SINGLE FAMILY

FIGURE 3.5

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

DOWNTOWN POWER PLANT



EQUALS 1 MILE

DOWNTOWN POWER PLANT

/ INDUSTRIAL

MF MULTI-FAMILY

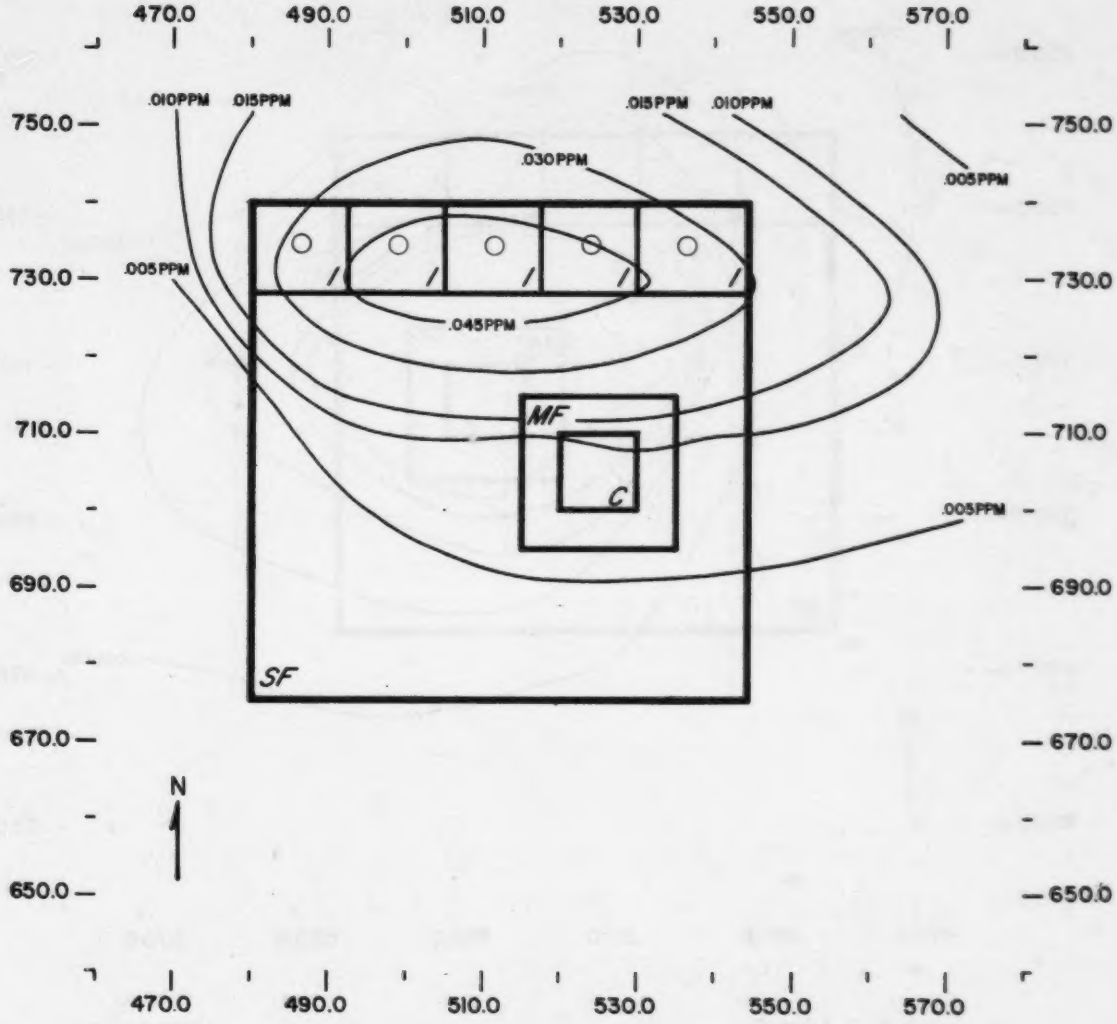
C COMMERCIAL

SF SINGLE FAMILY

FIGURE 3.6

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

INDUSTRIAL SOURCES



— EQUALS 1 MILE
○ INDUSTRIAL SOURCES

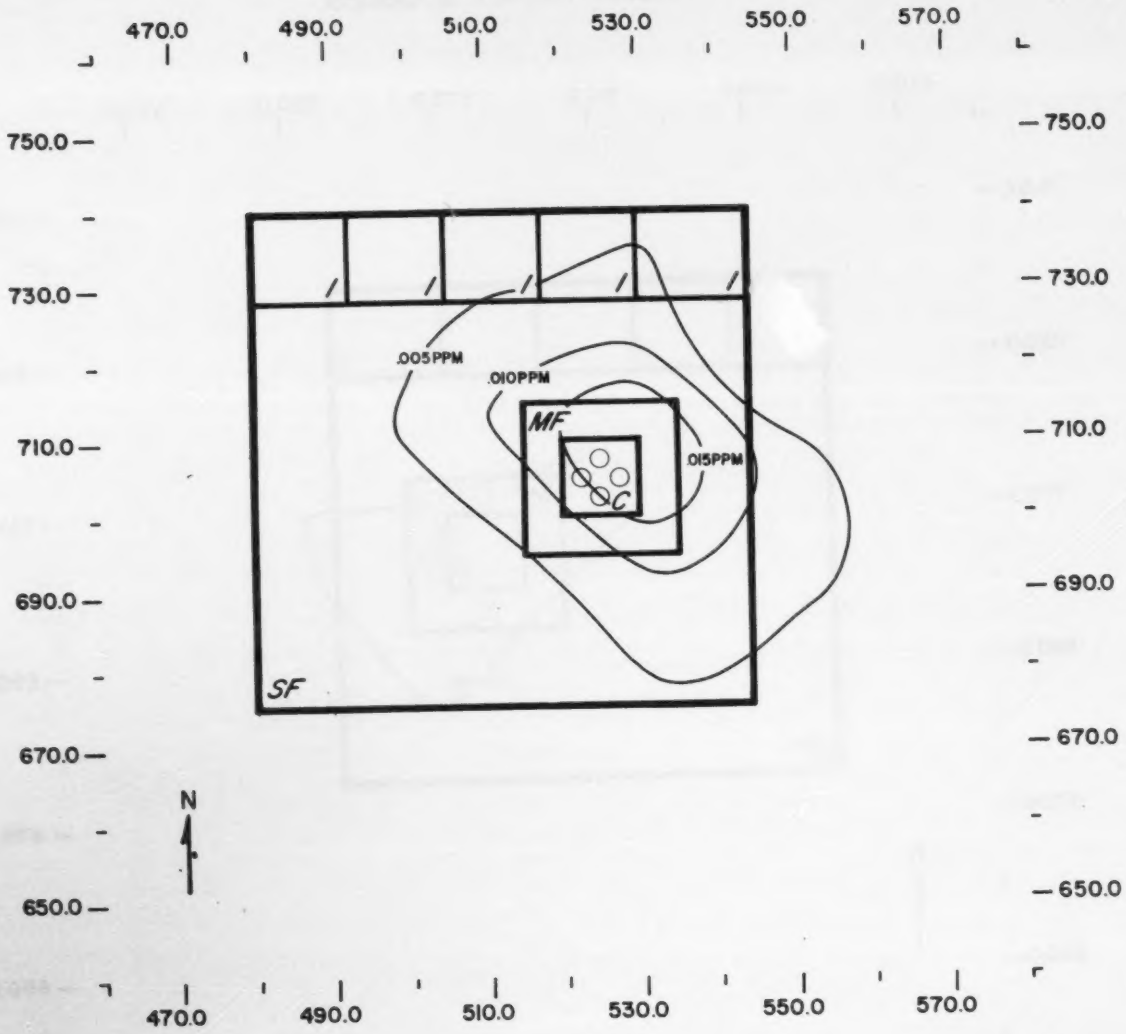
39<

/ INDUSTRIAL
MF MULTI-FAMILY
C COMMERCIAL
SF SINGLE FAMILY

FIGURE 3.7

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

COMMERCIAL SOURCES



EQUALS 1 MILE

COMMERCIAL SOURCES

/ INDUSTRIAL

MF MULTI-FAMILY

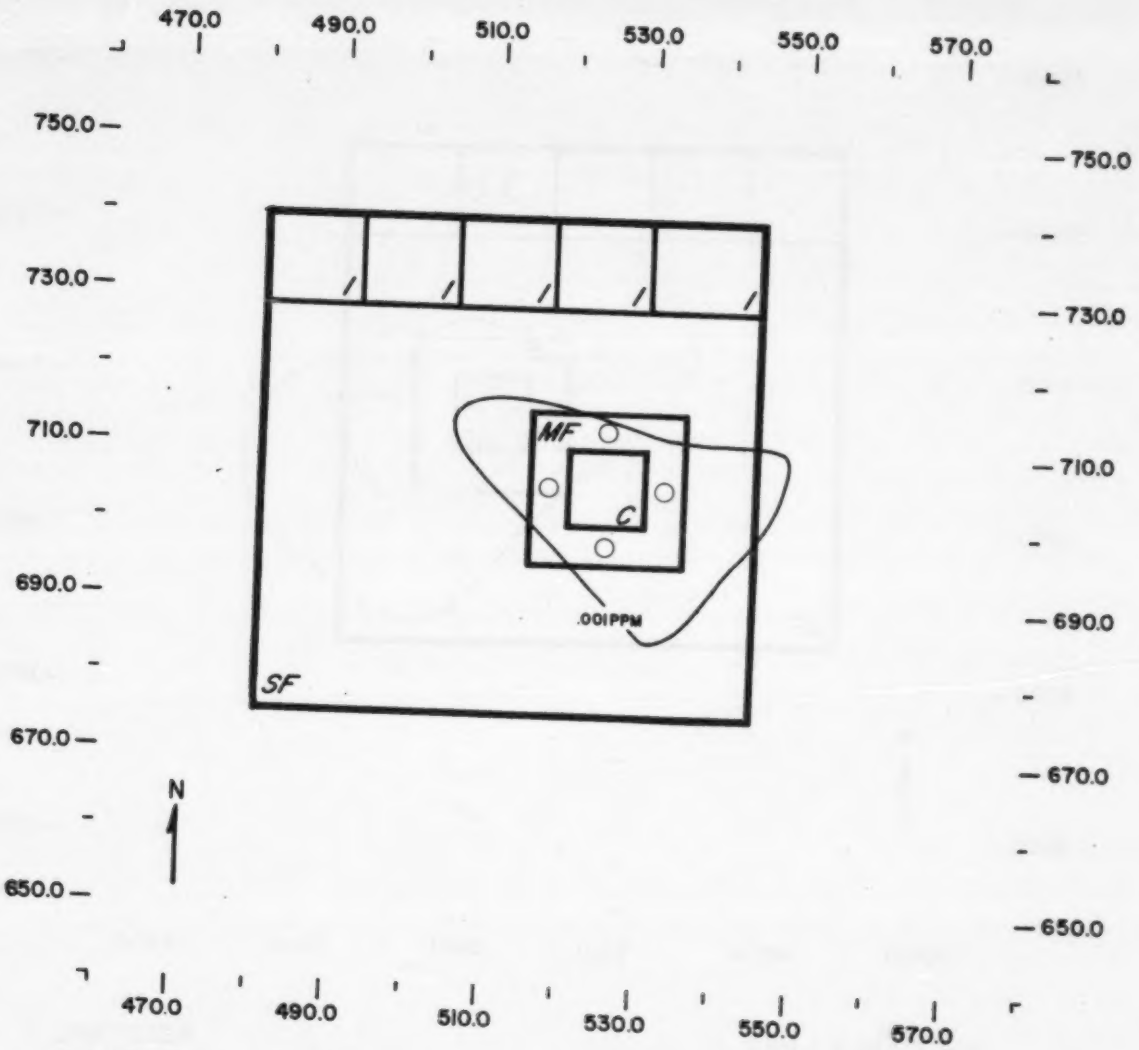
C COMMERCIAL

SF SINGLE FAMILY

FIGURE 3.8

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

MULTI-FAMILY SOURCES



⌊ EQUALS 1 MILE

○ MULTI-FAMILY SOURCES

/ INDUSTRIAL

MF MULTI-FAMILY

C COMMERCIAL

SF SINGLE FAMILY

it possible to look in detail at the impact of present research and development on the options available in the near future and at future costs of the various control methods.

1. Fuel Substitution

For large users, such as power plants and some industries, the selection of fuel is a complex problem involving compromises between availability, cost, location, assured supply, plant design, storage capability, flexibility needed, government regulations, expected future plans at that site, and more recently, air pollution. Since fuel selection for large users depends on such a wide variety of factors, it may not always be reasonable to assume that fuel switching is possible for pollution control. For smaller users, generally for space heating purposes, the choice is simpler and depends on the fuel available at the time the building or heating unit was built. New buildings use gas if available or No. 2 heating oil; older buildings often still use coal but have been converting to oil or gas. In this analysis, fuel switching was not allowed for any purposes. It was further assumed that users would be forced by nonpollution considerations to retain the original "mix" between coal, oil, and gas. In practice, of course, some fuel switching is often possible; the switch from coal or residual oil to natural gas is a very effective control method.

2. Fuel Desulfurization

Coal and residual oil may contain from 0.5 percent or less to more than 5 percent sulfur. However, there are available a variety of processes for removing sulfur from both. Residual oil may be desulfurized to any desired level but the practical lower limit is about 0.5 percent.

However, this severe processing may add up to 50 percent or more to the cost of the oil. Coal contains both organic sulfur, which is bound up with the carbon, and inorganic sulfur in the form of pyrites and sulfates. The ratio of organic to pyrite varies widely for different coals. Techniques are available only for removal of a portion of the pyrite; therefore a 50-percent limit on sulfur removal has been used for coal desulfurization in this study. In practice this might range from 10-percent to 75-percent sulfur removal for coal.

There is underway a large research and development effort on new methods for fuel desulfurization. It is expected that these will reduce substantially the cost of pyrite removal from coal in the near future and may make available within ten years practical, economical, low-sulfur pipeline gas from coal. There is little optimism that substantial economies can be made in desulfurizing residual oil or that simple processes can be developed for removing organic sulfur from coal.

3. Stack Gas Cleaning

Several processes for removing SO_2 from combustion gases are in the late stages of development. Most of these are applicable only to large new power plants and are designed to achieve a high degree of control. One, alkaline injection, shows some promise for existing power plants and large industrial boilers and may provide intermediate-to-good control. Sulfur is a valuable product and it is probable that the present massive research and development effort will result in the next ten years in processes which are economically self-liquidating for a variety of combustion sources. In this study, only processes now in the pilot-plant stage were included; these were assumed applicable to exiting power plants but not to industrial boilers.

4. Increased Stack Height

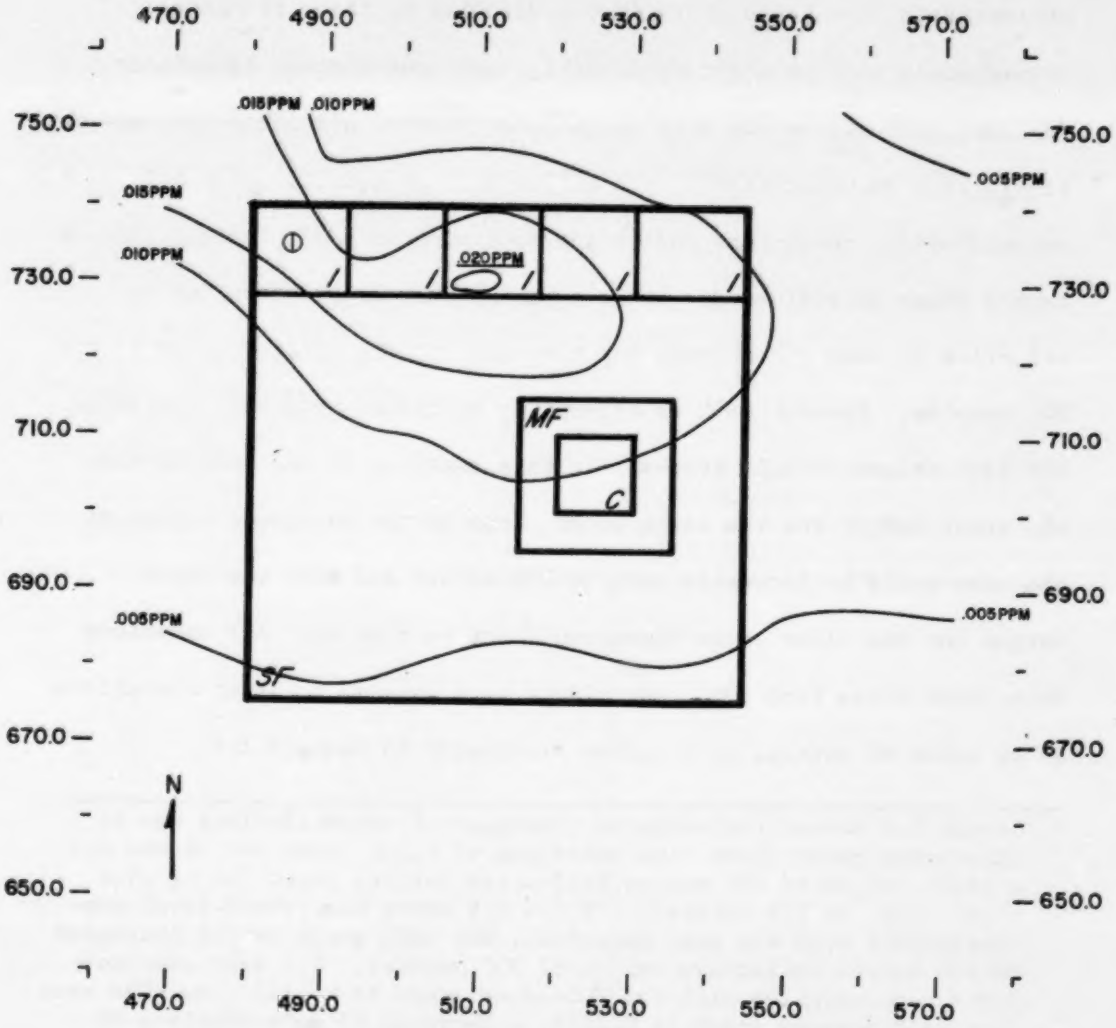
Stacks high enough to be effective for pollution dispersion are practical only for power plants, and their value in urban areas is questionable. The height may be limited by airway restrictions or by construction factors. Additional effective height may be obtained by increasing the temperature or the velocity of the exit gases. Considerable work is underway on design and construction techniques for very tall stacks for very large power plants, and large programs are in progress on understanding the diffusion that results under all meteorological conditions and on the determinations of chemical changes in the plume of effluents. It is apparent that high stacks can be effective in some situations, but they are not the entire answer to the SO_2 problem. Present work is attempting to define precisely the value and limitations of tall stacks. In this analysis it was assumed that the stack height for the large power plant in the northwest corner of the city could be increased only to 200 meters and that the stack height for the older power plant could not be changed. All emissions other than those from the power plants were assumed to be at elevations at or below 40 meters, as detailed previously in table 3.1.*

* Figure 3.4 showed the computed ground-level concentrations due to the uptown power plant with emissions of 4,000 grams per second and a stack height of 100 meters (effective height, stack height plus plume rise, is 165 meters). Figure 3.9 shows the ground-level concentrations with the same emissions, but with stack height increased to 200 meters (effective height of 330 meters). The mean receptor-point concentration with the 100-meter stack is 0.0123 ppm. The mean for the 200-meter stack is 0.0075, a decrease of approximately 40 percent. It is therefore assumed that, for the model city, increasing the stack height of the uptown power plant from 100 to 200 meters brings about an effective 40-percent decrease in the ground-level SO_2 concentrations it causes.

FIGURE 3.9

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

UPTOWN POWER PLANT (HIGH STACK)



EQUALS 1 MILE

① UPTOWN POWER PLANT WITH 200 METER STACK

/ INDUSTRIAL

MF MULTI-FAMILY

C COMMERCIAL

SF SINGLE FAMILY

5. Zoning and Relocation

The distribution and density of SO_2 sources are significant factors in urban air quality. In a given city these can be changed only by relocating existing sources and by zoning regulations for siting future sources. Since this analysis is of the current situation in the model city, zoning of future emission sources is not an appropriate technique for control. While the relocation of both power plants outside the urban area was not considered in the cost analysis, because of the much greater uncertainties in estimating the costs involved, the concentrations resulting from relocation are shown in Figure 3.19. Since no other significant single sources were specified for the model, other relocations were not considered .

The availability of each of the above techniques for SO_2 control is summarized in table 3.4. Techniques 1 and 2 above are combined in the table under "Intra-fuel substitution."

I. COSTS OF SO_2 CONTROL TECHNIQUES

The costs assumed for the SO_2 control techniques discussed in H above are given here and developed in more detail in Appendix B. It should be stressed that these costs are intended to be representative only of costs which might be encountered in practice. Many factors, not all of which have been considered here, enter into the determination of the costs, for example, of a ton of coal. Moreover, the wide differences in cost, particularly in the costs of coal delivered to two or more users of the same type in one area, may well be due more to noneconomic factors such as the bargaining capabilities of a purchasing agent in negotiating a contract, than to the simple determination

of quoted market price. Table 3.5 gives a brief summary of the maximum percentage reduction in emissions, and the cost thereof for each of the techniques.

Figures 3.10 through 3.14 show the estimated annual increased fuel costs to each type of consumer for reducing SO_2 emissions by substituting lower-sulfur coal for their present coal. Appendix B shows incremental costs for both natural low-sulfur coal and desulfurized low-sulfur coal from 1.5- to 1.0-percent sulfur content. It has been assumed that only the desulfurized low-sulfur coal would actually be available to consumers in the model city for sulfur content below 1.5 percent.

Figures 3.15 through 3.17 present similar information for residual oil consumers. Appendix B shows incremental costs for natural low-sulfur and desulfurized low-sulfur residual oil from 2.5 to 0.5 percent sulfur. It has been assumed that only the desulfurized low-sulfur residual oil would be available for sulfur contents less than 2.0 percent.

Figure 3.18 presents the estimated annual increased operating costs to the uptown and downtown power plants for reducing SO_2 emissions through the installation of stack gas cleaning equipment.

TABLE 3.4

AVAILABILITY OF TECHNIQUES FOR SO_2 CONTROL

SO_2 SOURCES	INTRA-FUEL SUBSTITUTION (LOW SULFUR FOR HIGH SULFUR, INCLUDING DESULFURIZATION)		STACK GAS CLEANING	INCREASED STACK HEIGHT
	COAL	RESIDUAL OIL		
Power Plants:				
Uptown	A	A	A	A
Downtown	A	NA	A	NA
Industrial	A	A	NA	NA
Commercial	A	A	NA	NA
Multi-family	A	NA	NA	NA

A = available

NA = not available

TABLE 3.5

SUMMARY OF MAXIMUM REDUCTION IN EMISSIONS AND COSTS RELATED THERETO

CONTROL TECHNIQUE	CONSUMER	MAXIMUM PERCENTAGE REDUCTION IN EMISSIONS	ESTIMATED ANNUAL INCREASED COSTS (000)
Intra-fuel substitution: Low-sulfur coal for high-sulfur coal	Power plants:		
	Uptown	80[1]	$4,940
	Downtown	80[1]	4,120
	Other:		
	Industrial	80[1]	2,100
	Commercial	67[1]	360
	Multi-family	67[1]	120
Low-sulfur residual oil for high-sulfur residual oil	Uptown power plant	80[2]	5,187
	Other:		
	Industrial	80[2]	3,045
	Commercial	80[2]	1,260
Stack gas cleaning	Power plants:		
	Uptown	90[3]	6,800
	Downtown	90[3]	5,100
High stack	Uptown power plant	40[4]	230

1/ Percentage reductions apply only to emissions resulting from combustion of coal.
2/ Percentage reductions apply only to emissions resulting from combustion of residual oil.
3/ Percentage reductions apply to all emissions from source.
4/ Effective reduction (see III, H, 4).

FIGURE 3.10

ESTIMATED ANNUAL INCREASED FUEL COSTS TO UPTOWN POWER PLANT FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR COAL FOR HIGH-SULFUR COAL

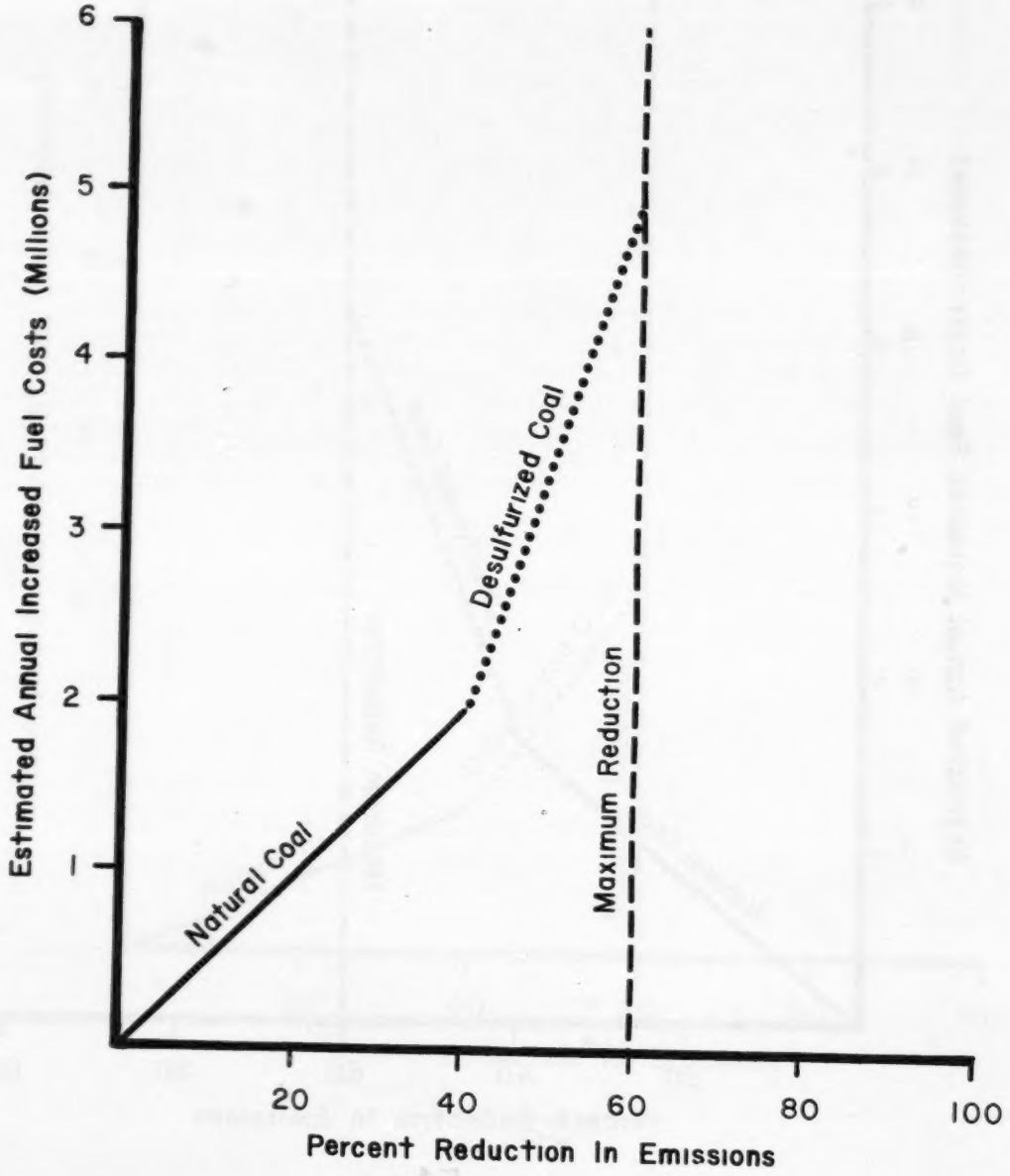


FIGURE 3.11

ESTIMATED ANNUAL INCREASED FUEL COSTS TO DOWNTOWN POWER PLANT FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR COAL FOR HIGH-SULFUR COAL

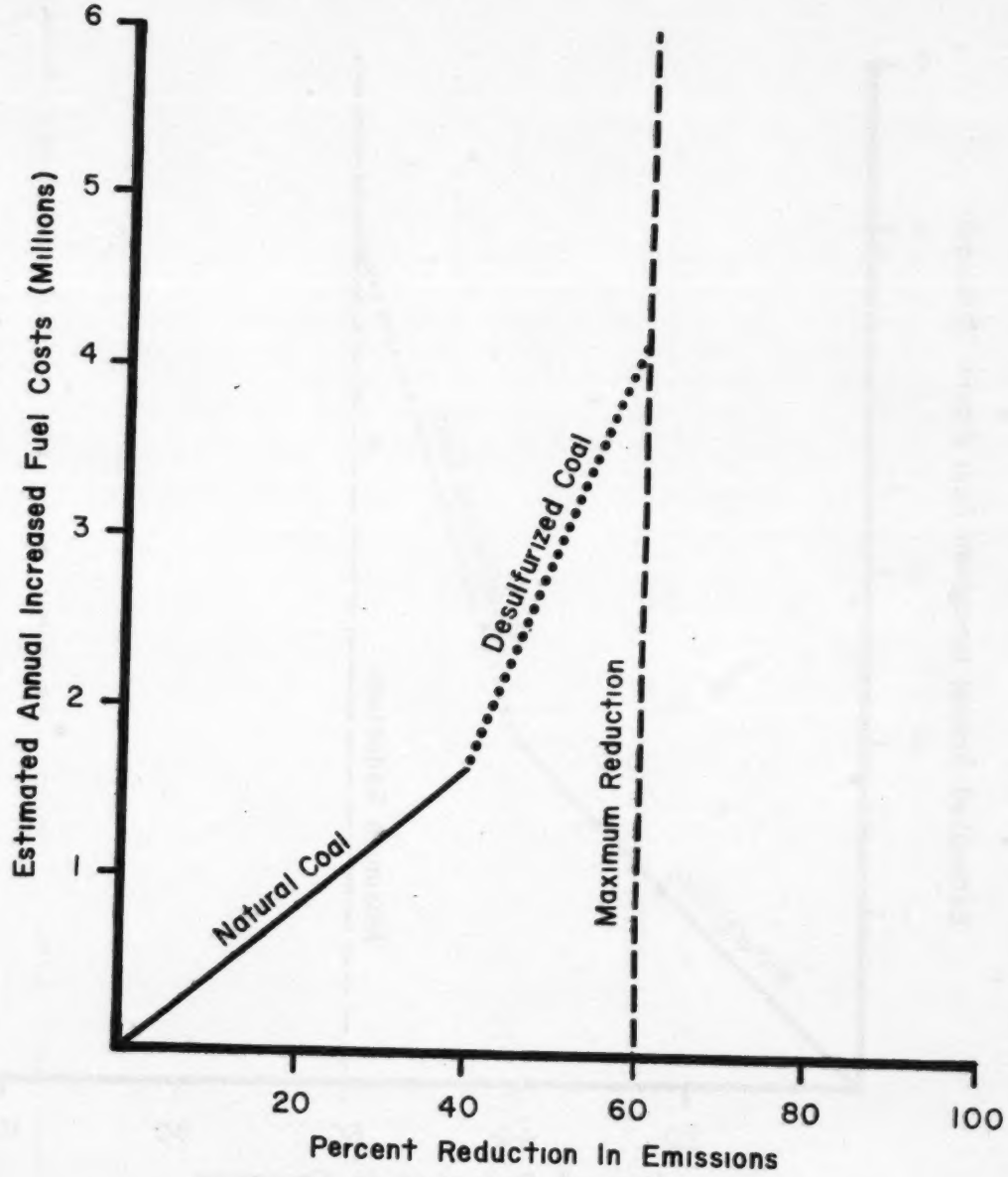


FIGURE 3.12

ESTIMATED ANNUAL INCREASED FUEL COSTS TO INDUSTRIAL SOURCES FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR COAL FOR HIGH-SULFUR COAL

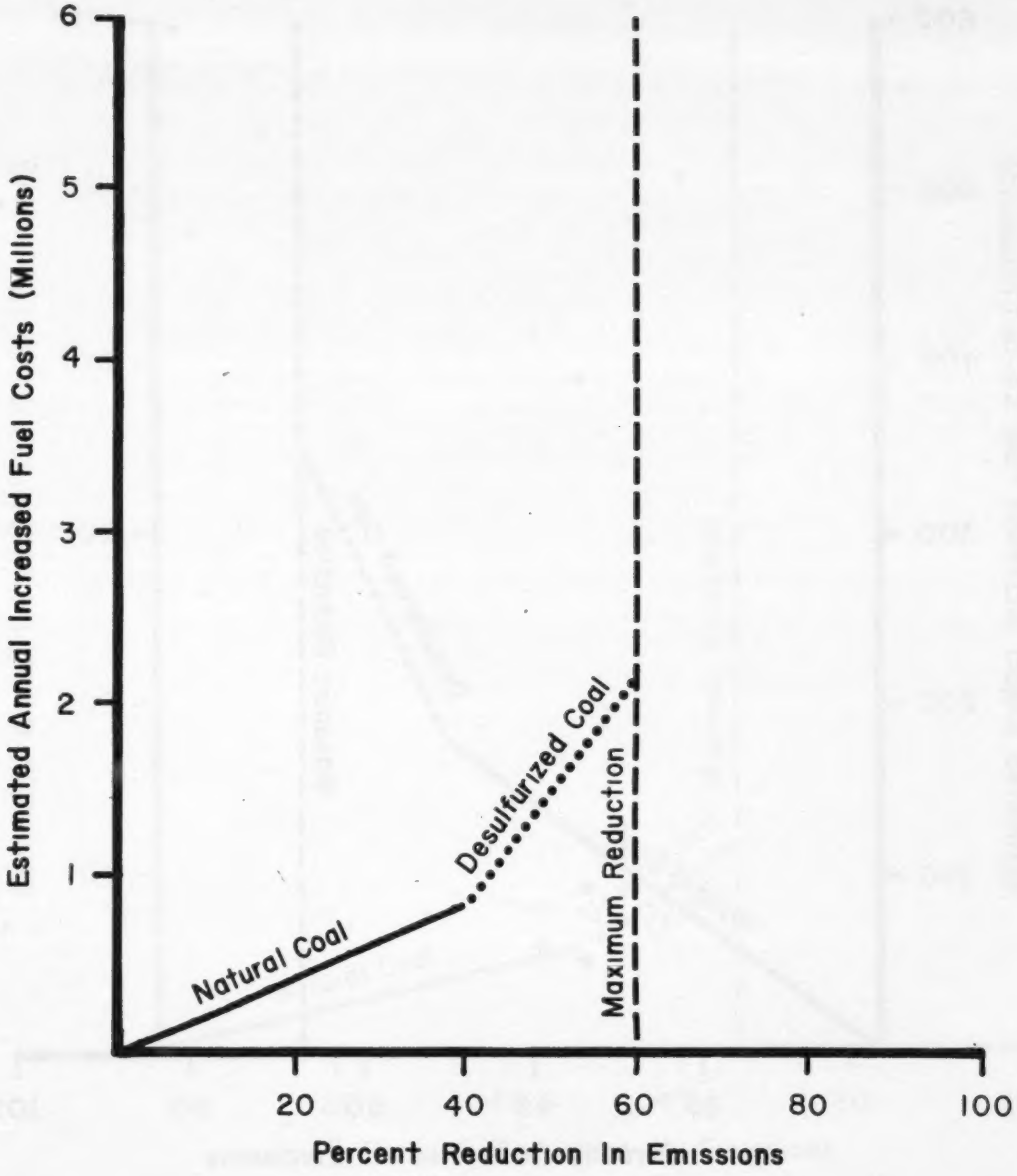


FIGURE 3.13

ESTIMATED ANNUAL INCREASED FUEL COSTS TO COMMERCIAL SOURCES FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR COAL FOR HIGH-SULFUR COAL

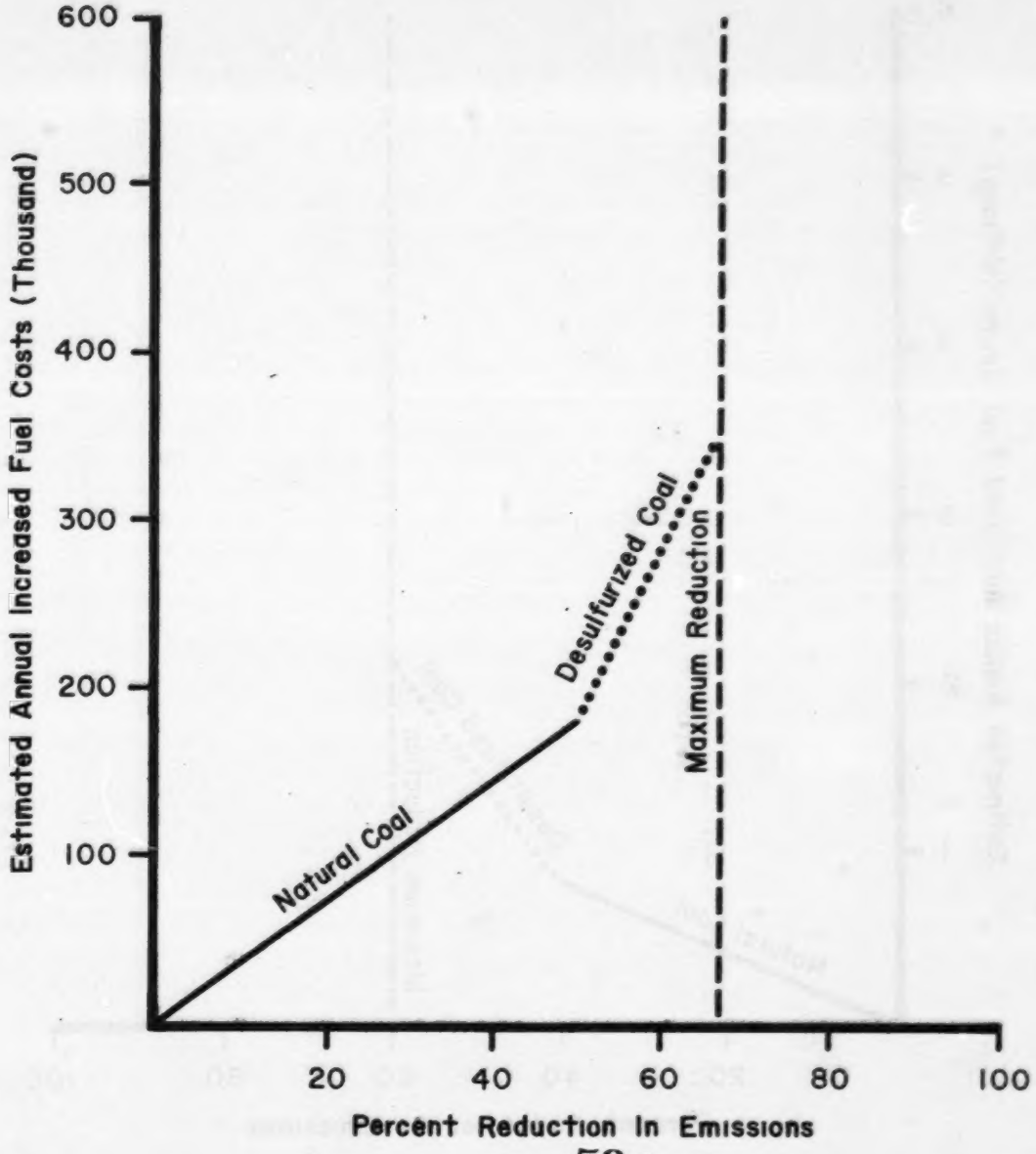


FIGURE 3.14

ESTIMATED ANNUAL INCREASED FUEL COSTS TO MULTI-FAMILY SOURCES FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR COAL FOR HIGH-SULFUR COAL

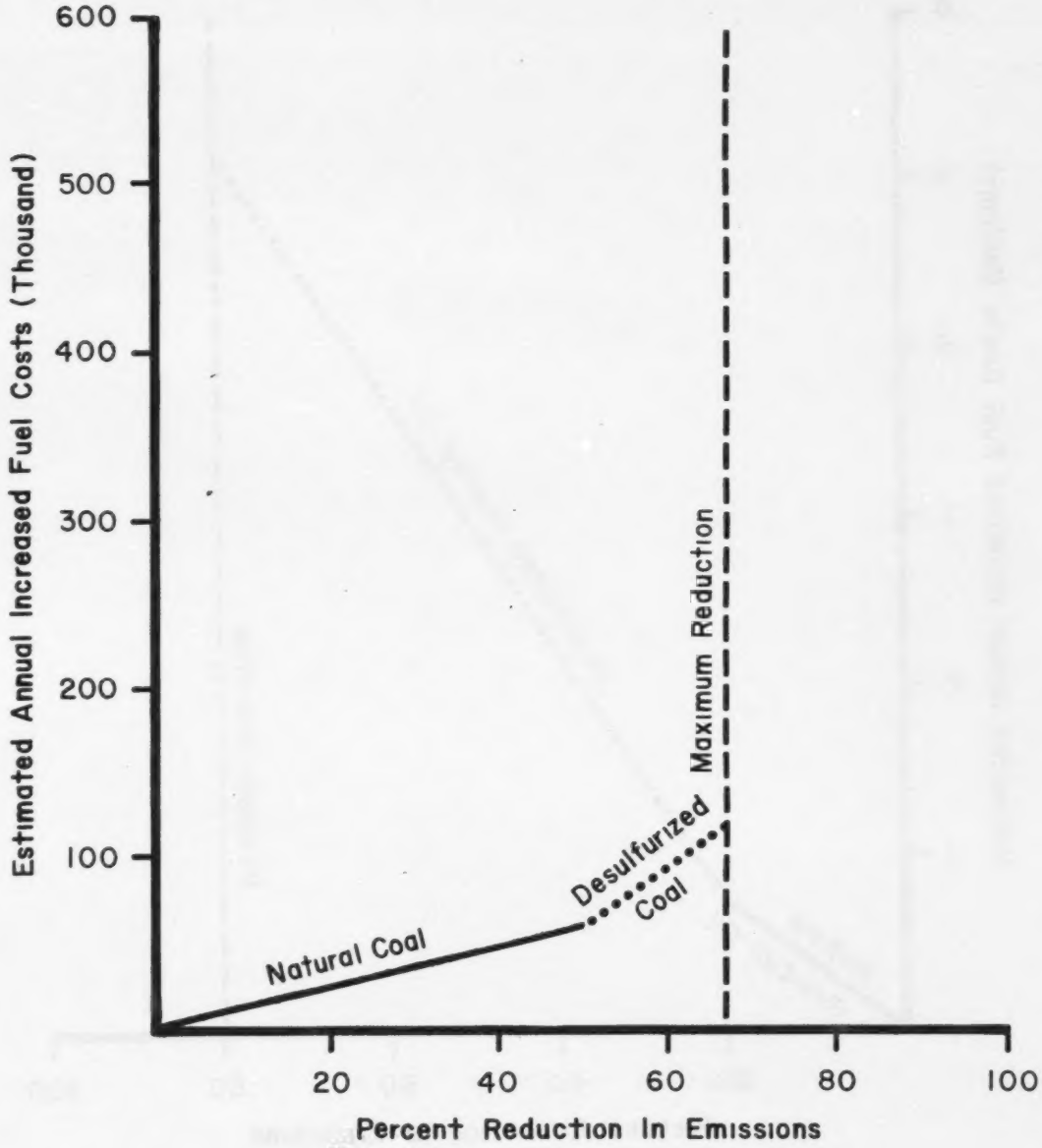


FIGURE 3.15

ESTIMATED ANNUAL INCREASED FUEL COSTS TO UPTOWN POWER PLANT FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR RESIDUAL OIL FOR HIGH-SULFUR RESIDUAL OIL

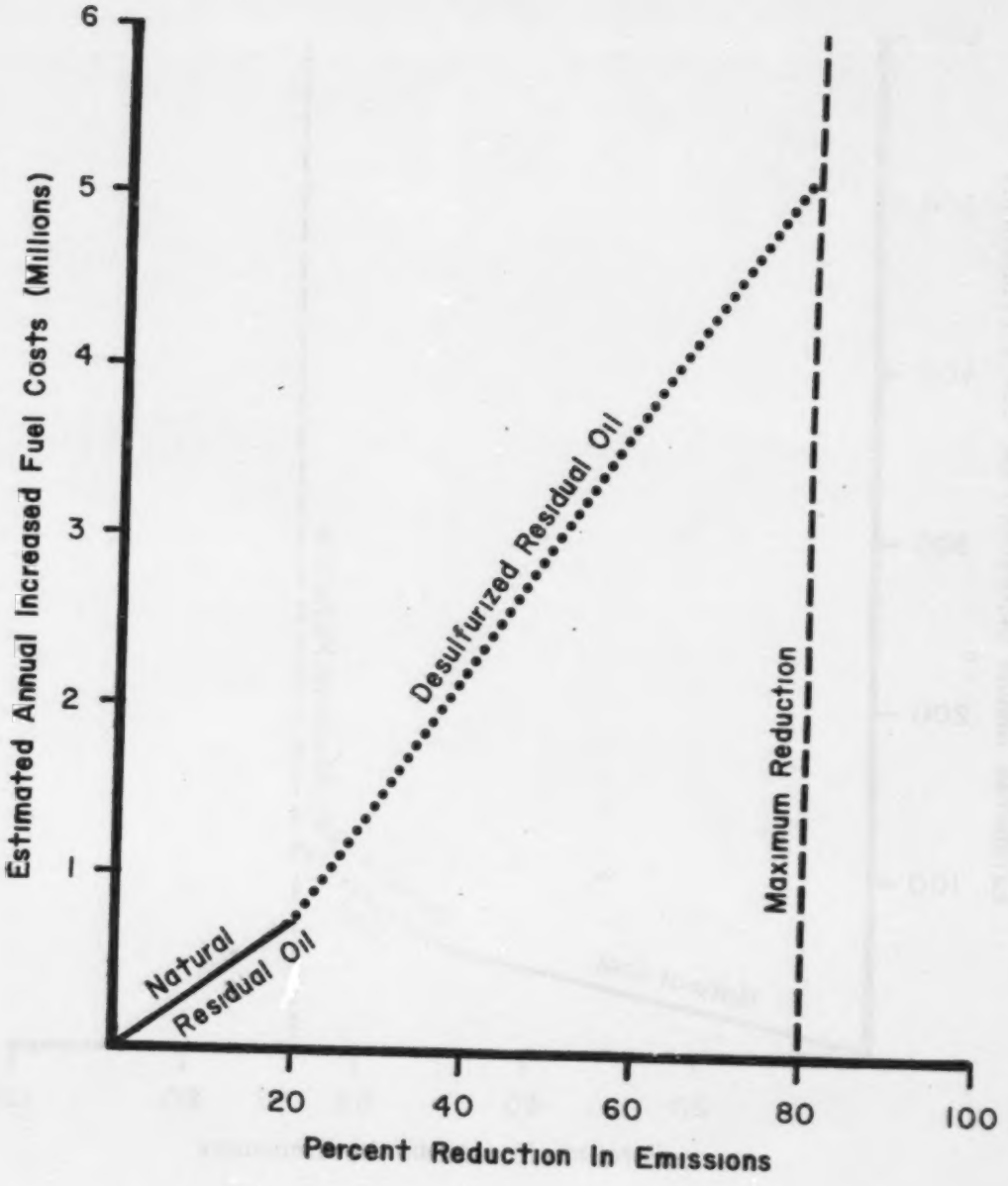


FIGURE 3.16

ESTIMATED ANNUAL INCREASED FUEL COSTS TO INDUSTRIAL SOURCES FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR RESIDUAL OIL FOR HIGH-SULFUR RESIDUAL OIL

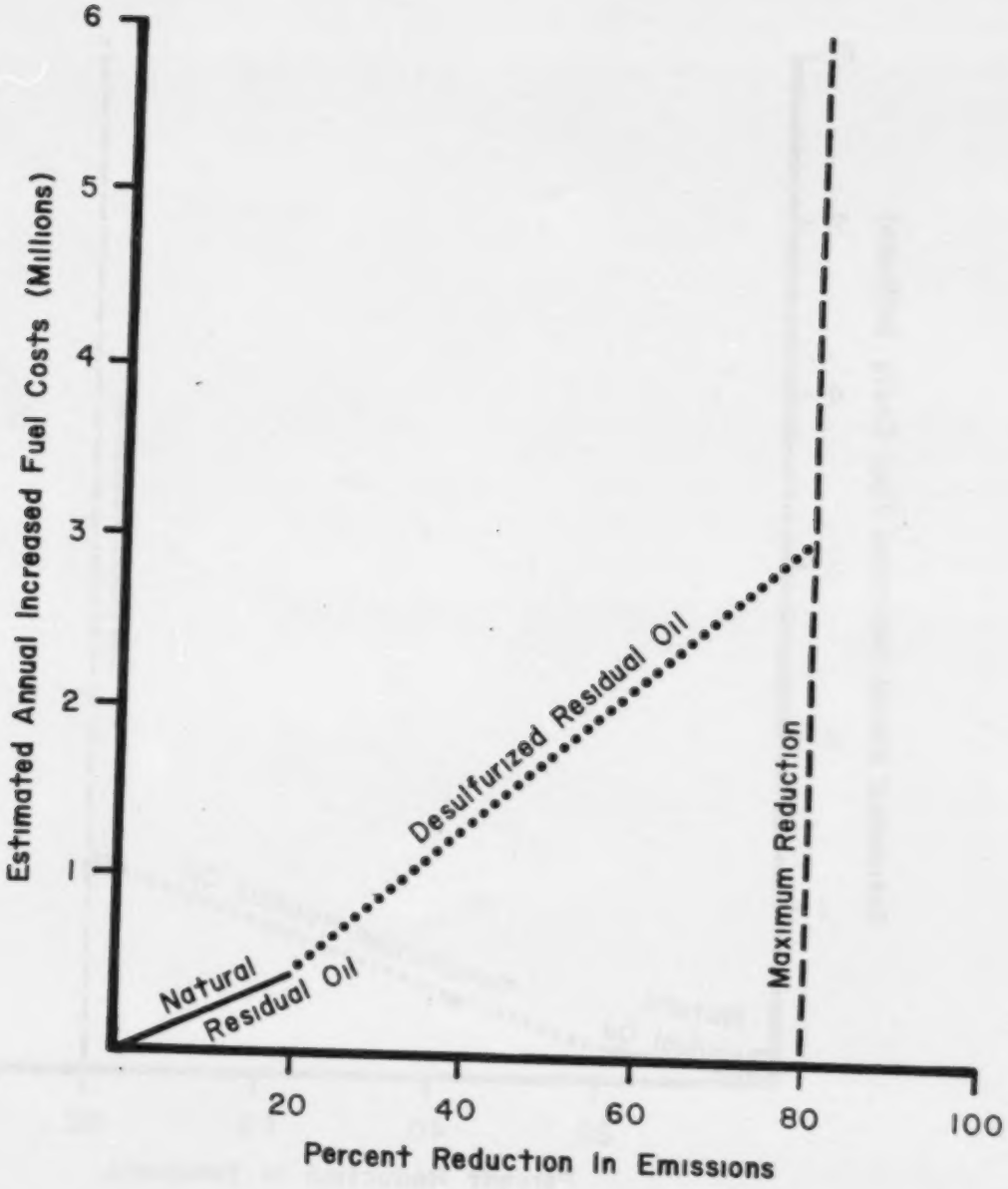


FIGURE 3.17

ESTIMATED ANNUAL INCREASED FUEL COSTS TO COMMERCIAL SOURCES FOR REDUCTION IN SO_2 EMISSIONS BY SUBSTITUTION OF LOW-SULFUR RESIDUAL OIL FOR HIGH-SULFUR RESIDUAL OIL

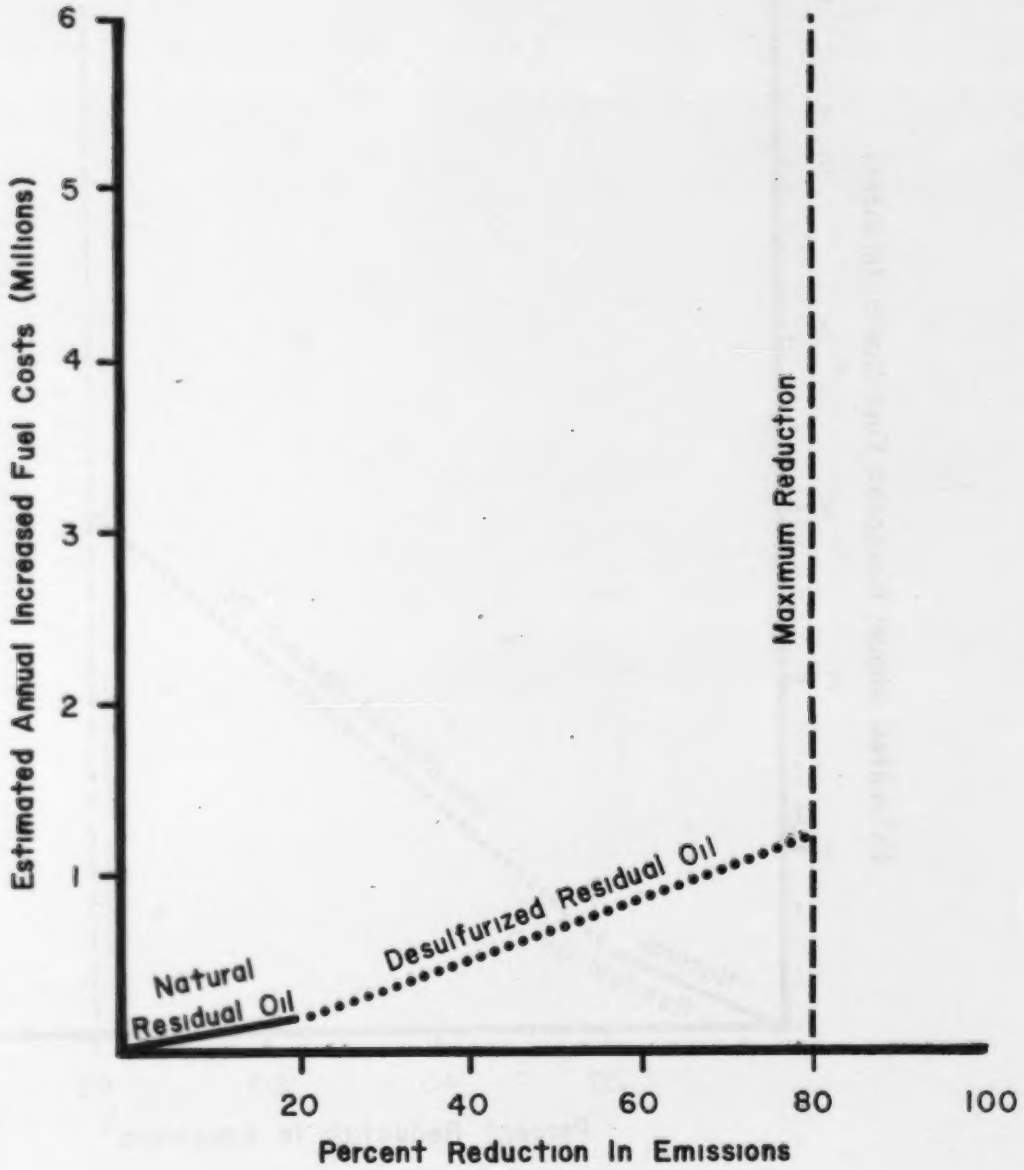
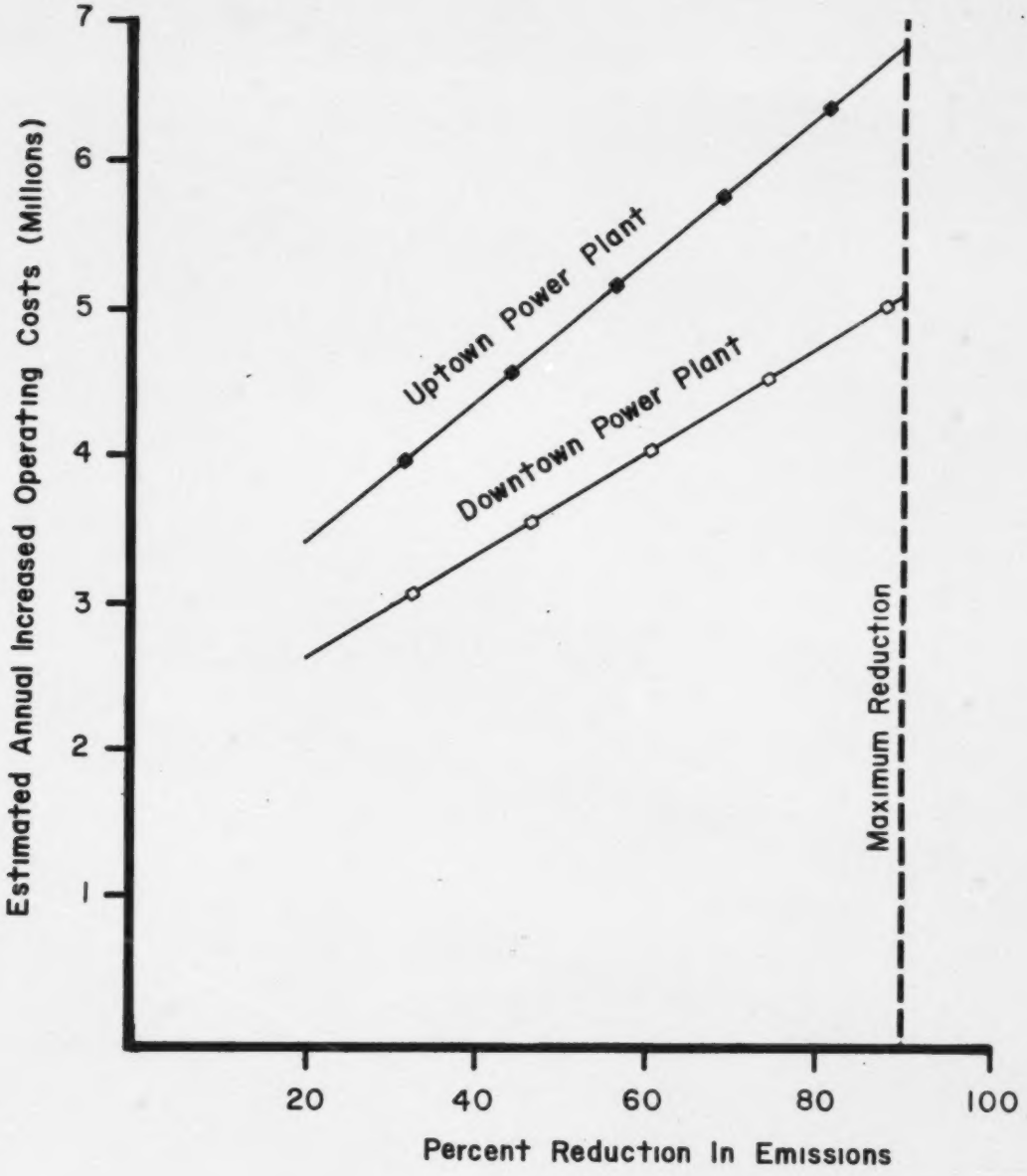


FIGURE 3.18

ESTIMATED ANNUAL INCREASED OPERATING COSTS TO POWER PLANTS FOR REDUCING SO_2 EMISSIONS BY INSTALLATION OF STACK GAS CLEANING EQUIPMENT



Estimated annual increased operating costs for the erection of a high (200 meter) stack at the uptown power plant, replacing the present low (100 meter) stack, amount to $230,000. (See Appendix B for calculations.)

TABLE 3.6

SELECTED FINANCIAL CHARACTERISTICS OF POWER PLANTS[1/]

	EXISTING PLANTS			NEW PLANT	POTENTIAL
	UPTOWN	DOWNTOWN	TOTAL	OUT OF TOWN	SAVINGS
Installed capacity--megawatts	1,600	1,200	2,800	2,800	
Plant investment per kilowatt installed	$150	$100	N/A	$115	
Total production plant investment (millions)	$240	$120	$360	$322	
Annual capital and other costs at 14 percent of investment (millions)	$ 33	$ 17	$ 50	$ 45	$ 5
Annual operating and maintenance expenses (millions)--production only, not including fuel	9	6	15	9	6
TOTAL	$ 42	$ 23	$ 65	$ 54	$11

1/ Not included herein are investment in transmission and distribution facilities, and annual operating and maintenance expenses associated therewith which are common to both existing and new plants. It has been assumed that these expenses will remain the same regardless of the location of the power plants, except for the cost of high-voltage transmission lines required from the new plant, which have been provided for in the cost of the new plant.

TABLE 3.7

ESTIMATED ANNUAL COSTS RELATED TO REPLACEMENT
OF EXISTING POWER PLANTS AND EFFECT ON POTENTIAL SAVINGS
(MILLIONS)

	OPTIMISTIC	PESSIMISTIC
Undepreciated cost (book value) of investment in plants	$150	$240
Average annual debt service 1/ requirements	$ 9	$ 14
Potential savings	11	11
Potential decrease in annual costs	$ 2	
Potential increase in annual costs		$ 3

1/ Serial bonds, due in equal annual installments over a period of thirty years, with interest at 5%.

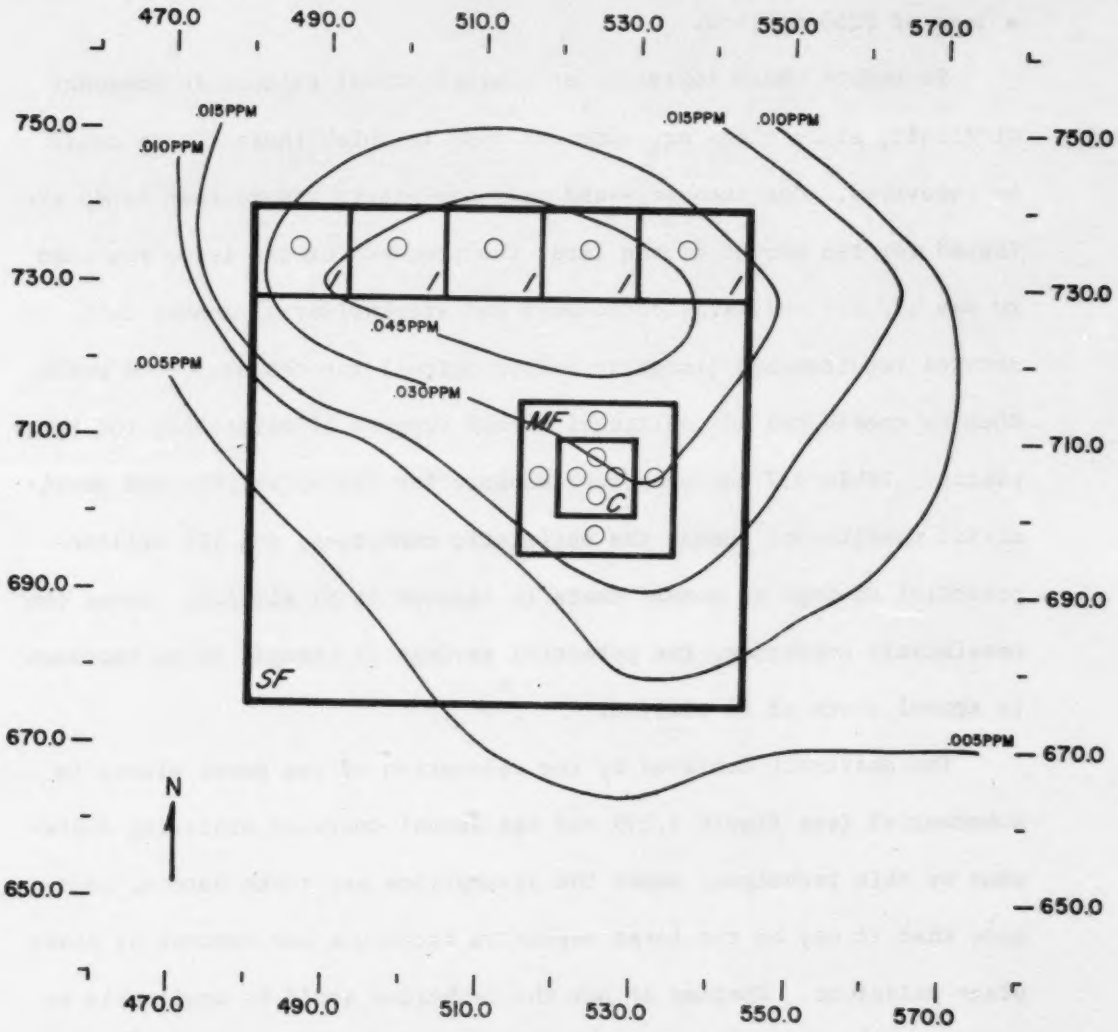
Under the pessimistic conditions, the undepreciated investment is $250 million. Replacement of the plants under the optimistic condition would result in a loss of $150 million; under the pessimistic condition, a loss of $250 million.

To relate these losses to an average annual expense is somewhat difficult, since there are numerous ways in which these losses could be recovered. One such way--and only one--is to assume that bonds are issued for the amount of the loss; the proceeds of the issue are used to pay off the existing bondholders and stockholders. Annual debt service requirements (interest and principal) for the new bonds would then be considered an additional annual expense of relocating the power plants. Table 3.7 includes such amounts for the optimistic and pessimistic conditions. Under the optimistic condition, the $11 million potential savings in annual costs is reduced to $2 million. Under the pessimistic condition, the potential savings is changed to an increase in annual costs of $3 million.

The abatement achieved by the relocation of the power plants is substantial (see figure 3.19) and the annual costs of achieving abatement by this technique, under the assumptions set forth herein, indicate that it may be the least expensive technique for control of power plant emissions. Whether or not the technique would be applicable to all situations is a question which cannot be answered here. It should be noted that, while this works very well for the model city, it has merely moved the emissions to another location, which may now be faced with the problem of control.

FIGURE 3.19

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)
ALL SOURCES (POWER PLANTS OUT OF TOWN)



EQUALS 1 MILE
ALL OTHER SOURCES

/ INDUSTRIAL
MF MULTI-FAMILY
C COMMERCIAL
SF SINGLE FAMILY

IV. MODEL CITY ABATEMENT OBJECTIVES AND STRATEGIES

This chapter presents the SO_2 abatement objectives which have been stipulated for the model city and the abatement strategies which have been selected to demonstrate the computational process involved in the simulation of urban SO_2 pollution abatement analysis.

A. ABATEMENT OBJECTIVES

Four distinct SO_2 abatement objectives have been stipulated for the model city:

1. Reduce the total average SO_2 emissions for the city by 20, 40, 60, 80, and maximum percentage.
2. Reduce the highest concentration point in the city by 20, 40, 60, 80, and maximum percentage.
3. Reduce the annual average concentrations in all parts of the city to 0.050 ppm or less as a first step in reduction to 0.015 ppm, the ultimate clean air objective.
4. Reduce human exposure to SO_2 in the city by 20, 40, 60, 80, and maximum percentage.

Objective 1 refers to table 3.3 of Chapter III and requires that the grand total emission of the model city, 10,005 grams per second, be reduced by the stated percentages.

Objective 2 refers to figure 3.3 of Chapter III and requires that the 0.316 ppm concentration computed for grid coordinates H-517.5 and V-712.5 be reduced by the stated percentages.

Objective 3 requires that all isopleths of figure 3.3 be reduced to 0.050 ppm or less. (While 0.015 ppm may be the ultimate target

under present air quality criteria,* a reduction to 0.050 ppm may be a reasonable short-term objective for the model city.)

Objective 4 requires that an appropriate measure of human exposure to different SO_2 concentrations be reduced by the stated percentages.

It should be noted that the objectives become increasingly sophisticated in their measure of abatement: Objective 1 demanding only reduction in emissions, Objectives 2 and 3 reductions in the concentrations caused by the emissions, and Objective 4 reductions in the exposure of people to the concentrations.

If realistic dollar values could be attached to the damage to people, animals, materials, and vegetation exposed to different SO_2 concentrations, and to the marginal economic activity associated with urban pollution, it would be reasonable to state a further objective seeking maximization of the net dollar benefit of SO_2 abatement. Although such an objective would be appealing in a cost-effectiveness analysis, the dollar-value damage functions are not available to make a proper analysis feasible.

B. ABATEMENT STRATEGIES

An abatement strategy is defined as a combination of available SO_2 control techniques applied to one or more emitting sectors of the model city; the emitting sectors being, as previously defined, the uptown power plant, the downtown power plant, the industrial

---

* Air Quality Criteria for Sulfur Oxides, op. cit.

sector, the commercial sector, and the multi-family dwelling sector. The available SO_2 control techniques postulated for the model city were discussed in Chapter III(H).

For the number of SO_2 control techniques available to the five emitting sectors of the model city (see table 3.4), there are a number of reasonable strategies which could be simulated, including the time phasing of control techniques. However, time has not allowed examination of all strategies, and therefore, only two strategies will be simulated. They are called the Equal-Proportional (EP) stragegy and the Least-Cost (LC) strategy. Both are applied to each objective.

1. Equal-Proportional (EP) Strategy

   This strategy is the minimum cost combination of SO_2 emission controls which achieves the same percentage emission reduction, no more and no less, at each of the fifteen point sources. It does not require uniform reduction in emissions from each of the fuels used at a source. For example, a 20-percent reduction in emissions from a point where the emissions are divided evenly between coal and residual oil may be accomplished by a 30-percent reduction in emissions from coal and a 10-percent reduction in emissions from oil. In applying the EP strategy, there is a choice among the several techniques for SO_2 control available to each emitting sector (see table 3.4).

In developing the costs of meeting each objective in Chapter V, the several combinations of emission control techniques for achieving equal-proportional control are given, including the lowest-cost combination. Since the lowest-cost combination under the EP strategy is constrained by the requirement to reduce all emissions at each source by the same percentage, its cost, as might be guessed, is generally higher than that of the LC strategy, which is not so constrained.

2. Least-Cost (LC) Strategy

The LC strategy is the minimum-cost combination of SO_2 emission controls which achieves no more and no less than the abatement objective. The minimum cost can be calculated in a particular situation by first determining the cost per gram/second (or ppm, or unit measure of exposure) reduced for each SO_2 control technique available to each emitting sector at each level of control. Second, the technique with the lowest unit cost is applied until its unit cost equals the next highest unit cost of another control technique. At this point, both are applied until the unit cost of one exceeds the other or until both unit costs exceed that of a third technique, and so on until the level of control is either achieved or approached as close as possible.

It will be seen in Chapter V that the computational procedure in applying the strategies becomes successively more complex from Objective 1 to Objective 4.

V. COST-EFFECTIVENESS OF ABATEMENT STRATEGIES

This chapter presents the estimated annual costs to be derived from achieving stated abatement objectives (the "effectiveness") by the alternative strategies described in the preceding chapter.

A. OBJECTIVE 1: REDUCE TOTAL EMISSIONS BY 20, 40, 60, 80, AND MAXIMUM PERCENT

1. Equal-Proportional Strategy

Table 5.1 shows, for each source, average annual emissions (grams per second) before control, average annual emissions at 20, 40, 60, and 80 percent and maximum control, the technique of achieving control, and the estimated annual costs thereof. Figure 5.1 shows the abated isopleths for maximum emission reduction.

2. Least-Cost Strategy

Table 5.2 shows information similar to table 5.1 for the least-cost strategy. The abated isopleths for maximum control in this case are the same as in figure 5.1.

3. Differences in Costs of Strategies

Figure 5.2 contrasts the differences in estimated annual costs between the EP and LC strategies applied to reducing total average annual emissions. The largest difference in cost between the two strategies is $3,065,000, which occurs at 20-percent reduction where the EP strategy costs $3,542,000 and the LC $477,000. At levels of reduction other than maximum, the lower total costs of the LC strategy should not

TABLE 5.1

COST OF REDUCING EMISSIONS BY
EQUAL-PROPORTIONAL STRATEGY

SOURCE	AVERAGE ANNUAL EMISSIONS GMS/SEC BEFORE REDUCTION	20% REDUCTION			40% REDUCTION			60% REDUCTION			80% REDUCTION 2/			MAXIMUM REDUCTION (89%)		
		AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST (000)
Power plants:																
Uptown	4,660	3,730	Fuel sub.	$1,641	2,795 1/	High stack	$ 230	1,865 1/	High stack with fuel sub.	$ 3,184	745 1/	High stack with stack clean.	$ 6,280	90 1/	High stack, stack clean. and fuel sub.	$17,157
Downtown	2,340	1,870	" "	824	1,405	Fuel sub.	1,648	935	Stack clean.	4,000	375	Stack clean.	4,920	95	Stack clean. and fuel sub.	9,220
TOTAL	7,000	5,600		2,465	4,200		1,878	2,800		7,184	1,120		11,200	185		26,377
Other sources:																
Industrial	2,280	1,820	Fuel sub.	813	1,365	Fuel sub.	2,145	915	Fuel sub.	4,275	695	Fuel sub.	5,145	695	Fuel sub.	5,145
Commercial	655	525	" "	240	395	" "	684	260	" "	1,188	160	" "	1,620	160	" "	1,620
Multi-family	70	55	" "	24	40	" "	48	30	" "	96	25	" "	120	25	" "	120
TOTAL	3,005	2,400		1,077	1,800		2,877	1,205		5,559	880		6,885	880		6,885
GRAND TOTAL	10,005	8,000		$3,542	6,000		$4,755	4,005		$12,743	2,000		$18,085	1,065		$33,262

1/ Effective, not absolute, reduction due to increased mixing height of effluents.

2/ 80% control cannot be achieved by sources other than the power plants.

TABLE 3.2

COST OF REDUCING EMISSIONS BY
LEAST-COST STRATEGY

SOURCE	AVERAGE ANNUAL EMISSIONS GMS/SEC BEFORE REDUCTION	20% REDUCTION			40% REDUCTION			60% REDUCTION			80% REDUCTION			MAXIMUM REDUCTION (89%)		
		AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST	AVERAGE ANNUAL EMISSIONS GMS/SEC	METHOD	ESTIMATED ANNUAL COST
				(000)			(000)			(000)			(000)			(000)
Power plants:																
Uptown (100-meter stack)	4,660	2,655 1/	High stack and fuel sub.	$477	2,490 1/	High stack and fuel sub.	$1,223	280 1/	High stack and stack cleaning	$7,030	280 1/	High stack and stack cleaning	$ 7,030	90 1/	High stack, stack cleaning, and fuel sub.	$17,153
Downtown	2,340	2,340	NC		1,405	Fuel sub.	1,648	1,615	Fuel sub.	1,278	235	Stack cleaning	5,100	95	Stack cleaning and fuel sub.	9,220
TOTAL	7,000	4,995		477	3,895		2,871	1,895		8,308	515		12,130	185		26,377
Other sources:																
Industrial	2,280	2,280	NC		1,585	Fuel sub.	1,275	1,585	Fuel sub.	1,275	1,120	Fuel sub.	1,426	695	Fuel sub.	5,145
Commercial	655	655	NC		485	Fuel sub.	324	485	Fuel sub.	324	340	Fuel sub.	900	160	Fuel sub.	1,620
Multi-family	70	70	NC		35	Fuel sub.	60	35	Fuel sub	60	25	Fuel sub.	120	25	Fuel sub.	120
TOTAL	3,005	3,005			2,105		1,659	2,105		1,659	1,485		2,446	880		6,885
GRAND TOTAL	10,005	8,000		$477	6,000		$4,530	4,000		$9,967	2,000		$16,576	1,065		$33,262

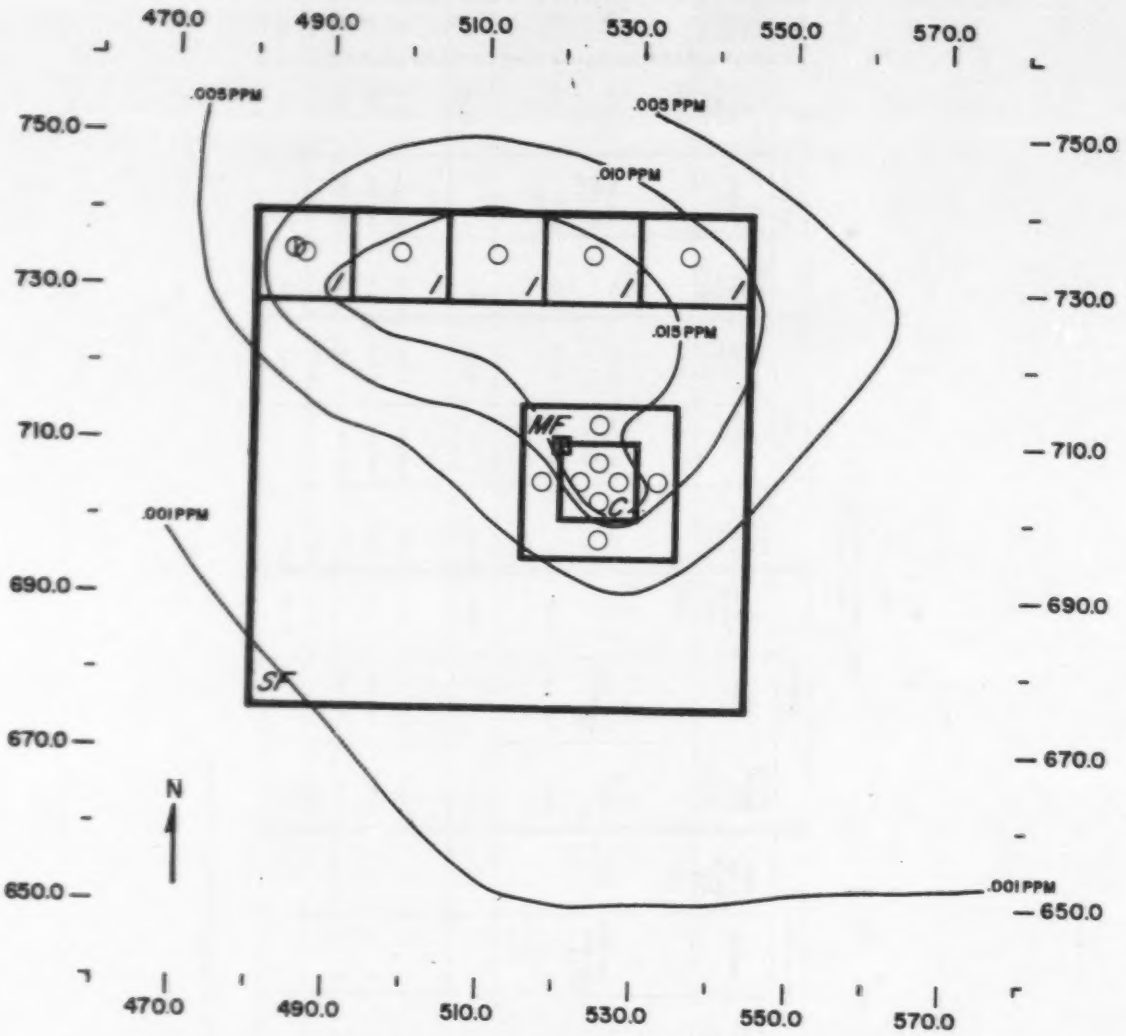
NC = No control

1/ Effective, not absolute, reduction due to increased mixing height of effluents.

FIGURE 5.1

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

ALL SOURCES, MAXIMUM REDUCTION



— EQUALS 1 MILE

⊕ UPTOWN POWER PLANT WITH 200 METER STACK

□ DOWNTOWN POWER PLANT

○ ALL OTHER SOURCES

/ INDUSTRIAL

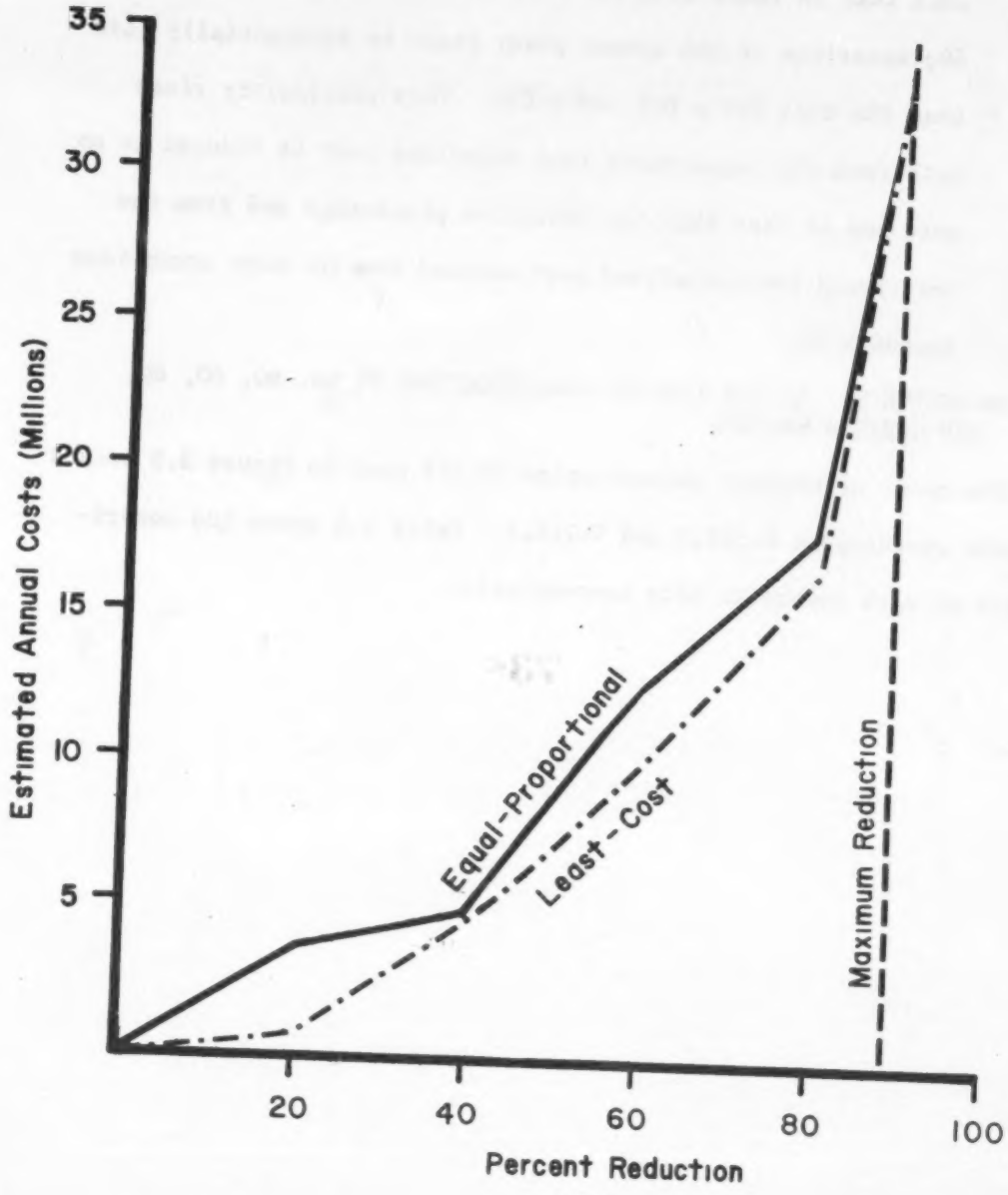
MF MULTI-FAMILY

C COMMERCIAL

SF SINGLE FAMILY

FIGURE 5.2

COMPARISON OF ESTIMATED ANNUAL COSTS OF REDUCING EMISSIONS — EQUAL-PROPORTIONAL AND LEAST-COST STRATEGIES



obscure the fact that the results of the two strategies are different in terms of the shape of the abatement isopleths, and therefore in terms of the damage effect on people, materials, and vegetation.

Note that in Table 5.1, the cost of reduction of 40% in the SO_2 emissions of the uptown power plant is substantially less than the cost for a 20% reduction. This peculiarity rises both from the requirement that emissions must be reduced to no more and no less than the objective percentage and from the relatively low annualized cost assumed for the high stack (see Appendix B).

B. OBJECTIVE 2: REDUCE HIGHEST CONCENTRATIONS BY 20, 40, 60, 80, AND MAXIMUM PERCENT

The point of highest concentration (0.316 ppm) in figure 3.3 occurs at grid coordinates H-517.5 and V-712.5. Table 5.3 shows the contribution of each source to this concentration.

1. Equal-Proportional Strategy

   Table 5.4 presents estimated annual costs of reducing the highest concentration by 20, 40, 60, 80, and 93 percent,* as well as the resultant average annual concentration at each level of control. The abated isopleths for 60-percent reduction are shown in figure 5.3.

2. Least-Cost Strategy

   Table 5.5 shows the estimated annual cost of reducing the highest concentration by the least-cost strategy by 20, 40, 60, 80, and 93 percent. This table shows resultant concentrations and contributions by source at each level of control, and the control techniques used. Figure 5.4 shows the abated isopleths for 60-percent reduction.

3. Differences in Costs of Strategies

   Figure 5.5 shows a comparison of the estimated annual costs of reducing the highest sulfur dioxide concentration by the EP strategy as opposed to the LC strategy. The differences in cost between these two strategies at almost all levels of control are substantial. The largest difference in cost between the two strategies is $9,871,000, which occurs at 80-percent reduction, where the EP strategy costs $18,085,000 and the LC $8,214,000. Again, the different shapes of the

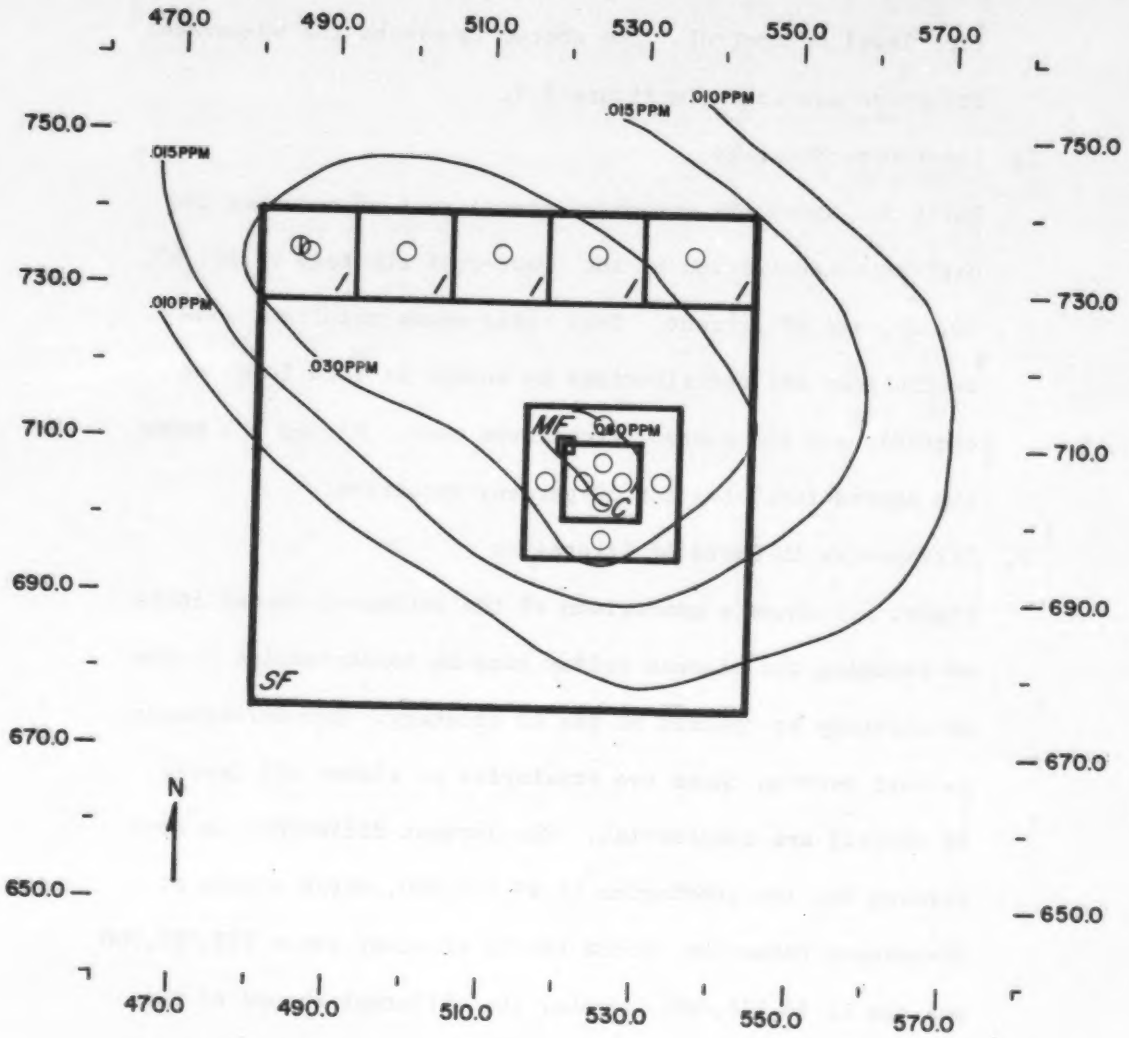
---

*A 93-percent reduction in the highest concentration is possible even though only 89-percent reduction in emissions can be achieved, because of the relative differences in the contributions to this concentration from each source.

FIGURE 5.3

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

ALL SOURCES, 60% EP REDUCTION



EQUALS 1 MILE

UPTOWN POWER PLANT WITH 200 METER STACK

DOWNTOWN POWER PLANT

ALL OTHER SOURCES

75<

/ INDUSTRIAL

MF MULTI-FAMILY

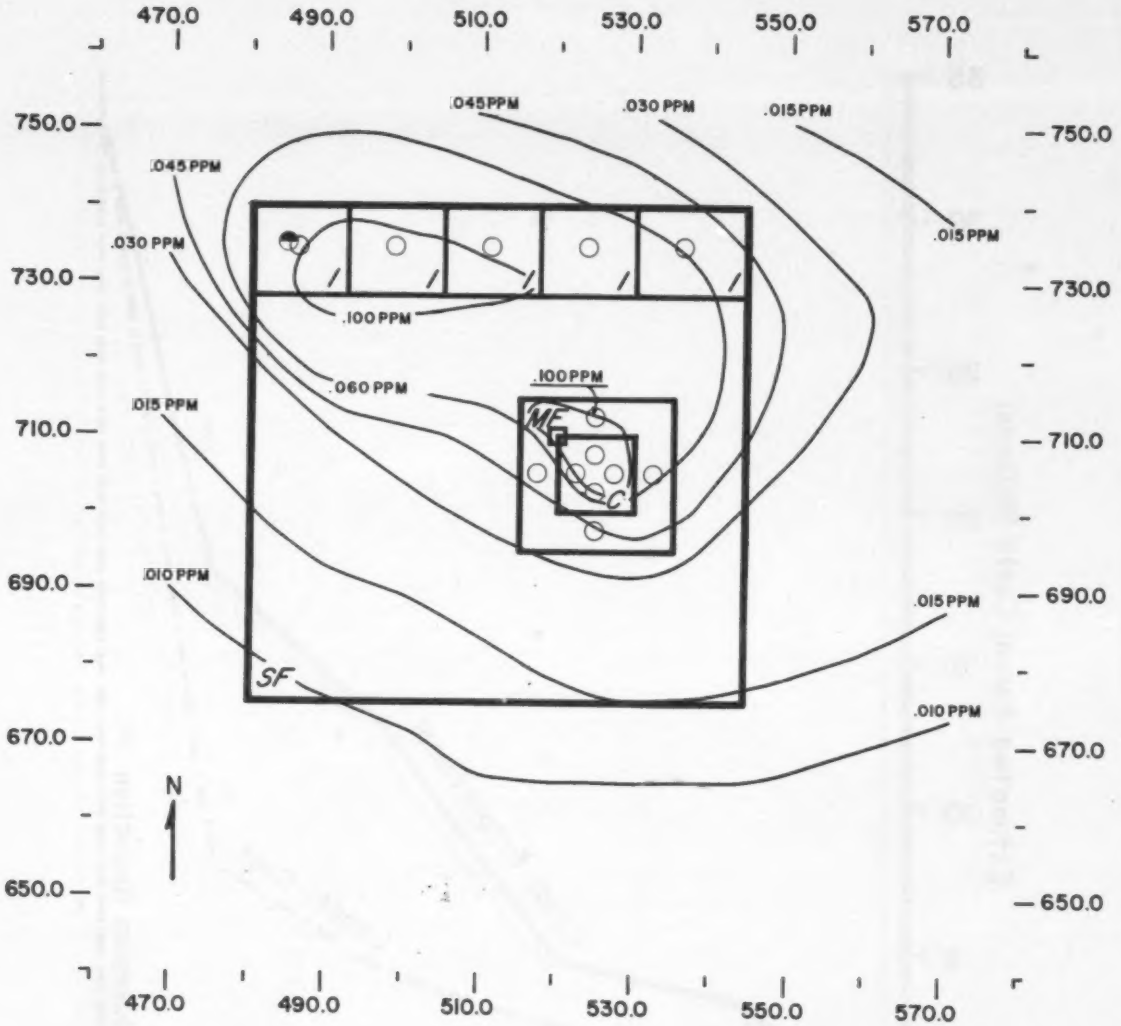
C COMMERCIAL

SF SINGLE FAMILY

FIGURE 5.4

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

ALL SOURCES, 60% LC REDUCTION



EQUALS 1 MILE
UPTOWN POWER PLANT WITH 100 METER STACK
DOWNTOWN POWER PLANT
ALL OTHER SOURCES

/ INDUSTRIAL
MF MULTI-FAMILY
C COMMERCIAL
SF SINGLE FAMILY

FIGURE 5.5

COMPARISON OF ESTIMATED ANNUAL COSTS OF REDUCING HIGHEST CONCENTRATION — EQUAL-PROPORTIONAL AND LEAST-COST STRATEGIES

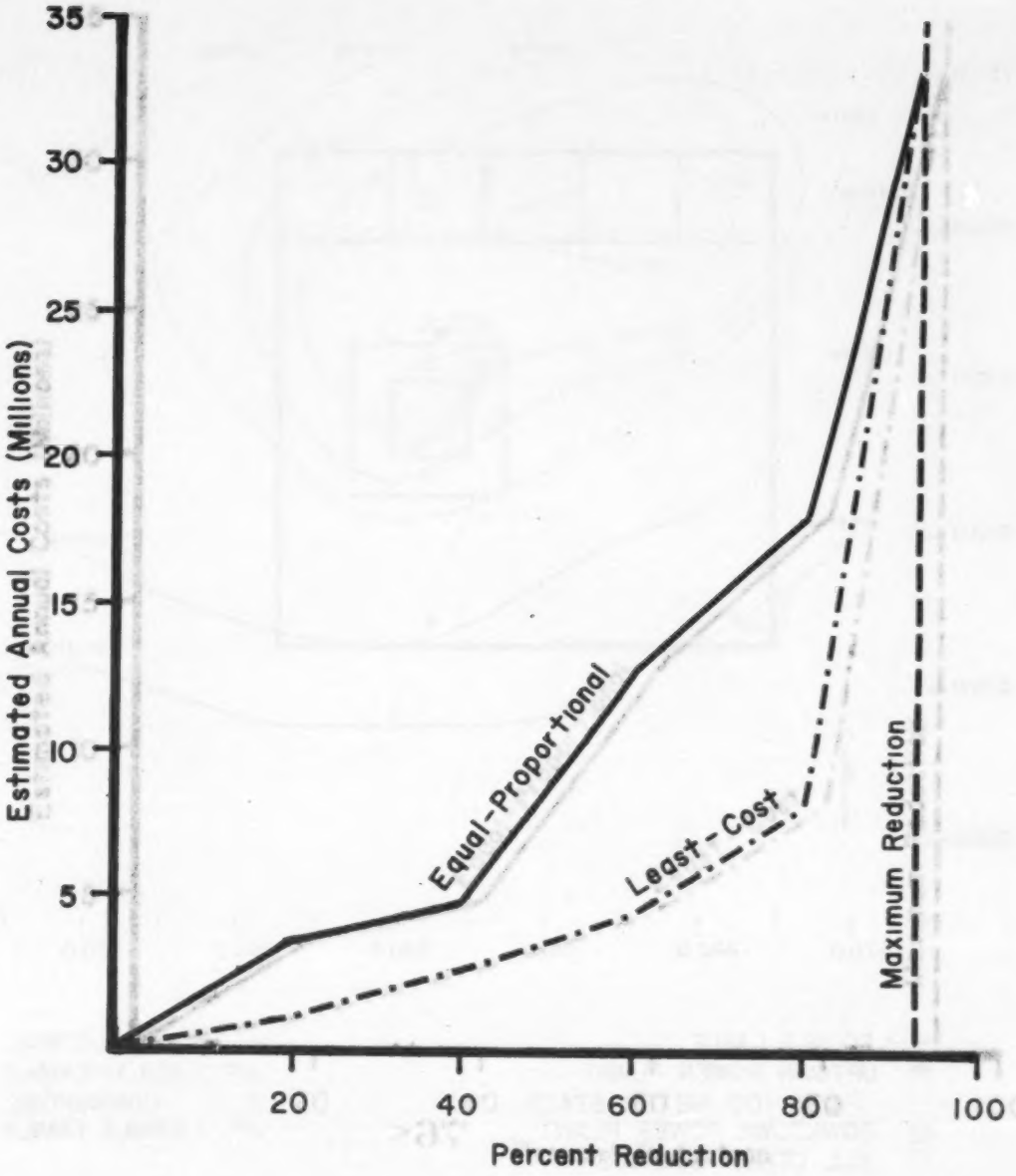


TABLE 5.4

REDUCTION OF HIGHEST CONCENTRATION
BY EQUAL-PROPORTIONAL STRATEGY

PERCENT REDUCTION	AVERAGE ANNUAL CONCENTRATIONS PPM	ESTIMATED ANNUAL COST 1/ (000)
0	0.316	---
20	0.253	$ 3,542
40	0.190	4,755
60	0.126	12,743
80	0.063	18,085
93	0.021	33,262

1/ From Table 5.1. The same techniques of reduction apply.

abated isopleths imply different damage effects. It should be noted also that the reduction in concentrations at various levels of control are substantial. As stated previously, the EP reduction produces equal reductions in all isopleths, while LC reduction affects only the isopleths of sources controlled. Since concentrations at all points are additive, a substantial reduction in the contribution of one source to a point concentration may have little or no effect on concentrations at other points.

TABLE 5.5

COST OF REDUCING HIGHEST CONCENTRATION
BY LEAST-COST STRATEGY

SOURCE	AV. ANNUAL CONCENTRATION BEFORE REDUCTION		20% REDUCTION				40% REDUCTION				60% REDUCTION				80% REDUCTION				MAXIMUM REDUCTION (97%)			
			CONCENTRATION		METHOD	EST. ANN. COST	CONCENTRATION		METHOD	EST. ANN. COST	CONCENTRATION		METHOD	EST. ANN. COST	CONCENTRATION		METHOD	EST. ANN. COST	CONCENTRATION		METHOD	EST. ANN. COST
	ppm	%	ppm	%		(000)	ppm	%		(000)	ppm	%		(000)	ppm	%		(000)	ppm	%		(000)
Power plants:																						
Uptown (100-meter stack)	0.018	5.4	0.018	7.1	NC		0.018	9.5	NC		0.018	14.3	NC		0.011 1/	17.5	High stack	$ 230	0.0005 1/	2.4	Maximum fuel sub. stack cleaning, and high stack	$17,157
Downtown	0.262	83.3	0.199	78.5	Fuel sub.	$989	0.136	71.6	Fuel sub.	$2,643	0.072	57.1	Stack cleaning	$4,520	0.016	25.4	Fuel sub. and stack cleaning	7,984	0.0105	50.0	Maximum fuel sub. and stack cleaning	9,220
TOTAL	0.280	88.7	0.217	85.8			0.154	81.1			0.090	71.4			0.027	42.9		8,214	0.0110	52.4		26,377
Other sources:																						
Industrial	0.012	3.6	0.012	4.7	NC		0.012	6.3	NC		0.012	9.5	NC		0.012	19.0	NC		0.0040	19.0	Maximum fuel sub.	5,145
Commercial	0.021	6.6	0.021	8.3	NC		0.021	11.0	NC		0.021	16.7	NC		0.021	33.3	NC		0.0050	23.8	" "	1,620
Multi-family	0.003	1.1	0.003	1.2	NC		0.003	1.6	NC		0.003	2.4	NC		0.003	4.8	NC		0.0010	4.8	" "	120
TOTAL	0.036	11.3	0.036	14.2			0.036	18.9			0.036	28.6			0.036	57.1			0.0100	47.6		6,885
GRAND TOTAL	0.316	100.0	0.253	100.0		$989	0.190	100.0		$2,643	0.126	100.0		$4,520	0.063	100.0		$8,214	0.0210	100.0		$ 33,262

NC = No control.

1/ Effective, not absolute, reduction due to increased mixing height of effluents.

C. OBJECTIVE 3: REDUCE ALL CONCENTRATIONS TO 0.050 PPM OR LESS

Table 5.6 shows the location of the receptor points within the model city with concentrations in excess of 0.050 ppm, total concentrations at these points, and contributions to these concentrations from each of the sources.

1. Equal-Proportional Strategy

Table 5.7 lists all receptor points with average annual concentrations in excess of 0.050 ppm and shows the percentage reduction in the concentrations necessary to reach 0.050 ppm. Table 5.8 shows the percent contribution of all sources at each one of the points listed on table 5.7. From these, it is possible to conclude that an EP strategy for reduction in all concentrations to 0.050 ppm is not practical. First, not all sources can attain 80- to 90-percent reduction in emissions, and second, the proportionate contributions of the sources to the concentration at a receptor point vary widely. This implies there is no single reduction, short of 80 to 90 percent, which can be applied uniformly to all sources to bring all receptor point concentrations to 0.050 ppm or less.

2. Least-Cost Strategy

Table 5.9 shows the estimated annual cost to all sources and the total cost of reducing all concentrations within the model city to 0.050 ppm or less. The table also shows the techniques for achieving reduction and the percentage

TABLE 5.6

CONCENTRATIONS IN EXCESS OF 0.050 ppm

COORDINATES		POWER PLANTS			OTHER SOURCES				TOTAL ALL SOURCES
HORIZ.	VERT.	UPTN.	DNTN.	TOTAL	IND.	COMM.	M.F.	TOTAL	
470.0	750.0	0.046	0.005	0.051	0.011	0.001	N	0.012	0.063
490.0	750.0	.030	.007	.037	.021	.002	N	.023	.060
490.0	730.0	.075*	.010	.085	.044	.002	N	.046	.131
510.0	750.0	.014	.011	.025	.027	.003	N	.030	.055
510.0	730.0	.039	.027	.066	.058*	.005	N	.063	.129
510.0	710.0	.020	.040	.060	.010	.009	0.001	.020	.080
530.0	730.0	.018	.011	.029	.046	.006	.001	.053	.082
530.0	710.0	.015	.104	.119	.011	.020	.006*	.037	.156
517.5	712.5	.018	.262*	.280	.012	.021	.003	.036	.316
517.5	697.5	.011	.031	.042	.006	.005	.002	.013	.055
722.5	707.5	.014	.172	.186	.010	.076	.003	.089	.275
722.5	702.5	.012	.070	.082	.008	.039	.006*	.053	.135
527.5	707.5	.013	.144	.157	.009	.091*	.005	.105	.262
527.5	702.5	.011	.073	.084	.007	.082	.003	.092	.176
532.5	712.5	.016	.049	.065	.013	.010	.004	.027	.092
532.5	697.5	.009	.035	.044	.006	.021	.003	.030	.074

*Highest individual concentrations from source indicated.

TABLE 5.7

PERCENT REDUCTIONS NECESSARY TO REDUCE CONCENTRATIONS BEFORE CONTROL TO 0.050 ppm OR LESS

COORDINATES		TOTAL CONCENTRATION BEFORE REDUCTION	PERCENT REDUCTION TO ACHIEVE 0.050 ppm
HORZ.	VERT.		
517.5	712.5	0.316	84.2
722.5	707.5	.275	81.8
527.5	707.5	.262	80.9
527.5	702.5	.176	71.5
530.0	710.0	.156	67.9
722.5	702.5	.135	63.0
490.0	730.0	.131	61.8
510.0	730.0	.129	61.2
532.5	712.5	.092	45.6
530.0	730.0	.082	39.0
510.0	710.0	.080	37.5
532.5	697.5	.074	32.4
470.0	750.0	.063	20.6
490.0	750.0	.060	16.7
517.5	697.5	.055	9.1
510.0	750.0	.055	9.1

TABLE 5.8

PERCENT CONTRIBUTIONS OF ALL SOURCES TO CONCENTRATIONS IN EXCESS OF 0.050 ppm

COORDINATES		POWER PLANTS			OTHER SOURCES				TOTAL ALL SOURCES
HORIZ.	VERT.	UPTN.	DNTN.	TOTAL	IND.	COMM.	M.F.	TOTAL	
517.5	712.5	5.6	83.0	88.6	3.8	6.6	1.0	11.4	100.0
722.5	707.5	5.1	62.5	67.6	3.6	27.8	1.0	32.4	100.0
527.5	707.5	5.0	55.0	60.0	3.4	34.7	1.9	40.0	100.0
527.5	702.5	6.3	41.5	47.8	4.0	46.5	1.7	52.2	100.0
530.0	710.0	9.6	66.6	76.2	7.1	12.8	3.9	23.8	100.0
722.5	702.5	8.9	51.8	60.7	5.9	28.9	4.5	39.3	100.0
490.0	730.0	57.2	7.7	64.9	33.6	1.5	N	35.1	100.0
510.0	730.0	30.2	20.9	51.1	45.0	3.9	N	48.9	100.0
532.5	712.5	17.4	53.2	70.6	14.1	10.9	4.4	29.4	100.0
530.0	730.0	22.0	13.4	35.4	56.1	7.3	1.2	64.6	100.0
510.0	710.0	25.0	50.0	75.0	12.5	11.3	1.2	25.0	100.0
532.5	697.5	12.2	47.3	59.5	8.1	28.4	4.0	40.5	100.0
470.0	750.0	73.0	8.0	81.0	17.5	1.5	N	19.0	100.0
490.0	750.0	50.0	11.7	61.7	35.0	3.3	N	38.3	100.0
517.5	697.5	20.0	56.4	76.4	10.9	9.1	3.6	23.6	100.0
510.0	750.0	25.5	20.0	45.5	49.1	5.4	N	54.5	100.0

Table 5.9

COST OF REDUCING CONCENTRATIONS
TO 0.050 ppm OR LESS-LEAST-COST STRATEGY

SOURCE	TECHNIQUE FOR REDUCTION	ESTIMATED ANNUAL COST (000)	EMISSIONS (GMS/SEC) BEFORE REDUCTION	AFTER REDUCTION	PERCENT REDUCTION
Power plants:					
Uptown	High stack and fuel sub.	$ 2,038	4,660	2,180	53.2%
Downtown	Stack gas cleaning	5,100	2,340	235	90.0
		7,138	7,000	2,415	65.5
Other sources:					
Industrial	Maximum fuel sub.	5,145	2,280	695	69.5
Commercial	" " "	1,620	655	160	75.6
Multi-family	" " "	120	70	25	64.2
		7,885	3,005	880	70.7
		$15,023	10,005	3,295	67.1%

Table 5.10

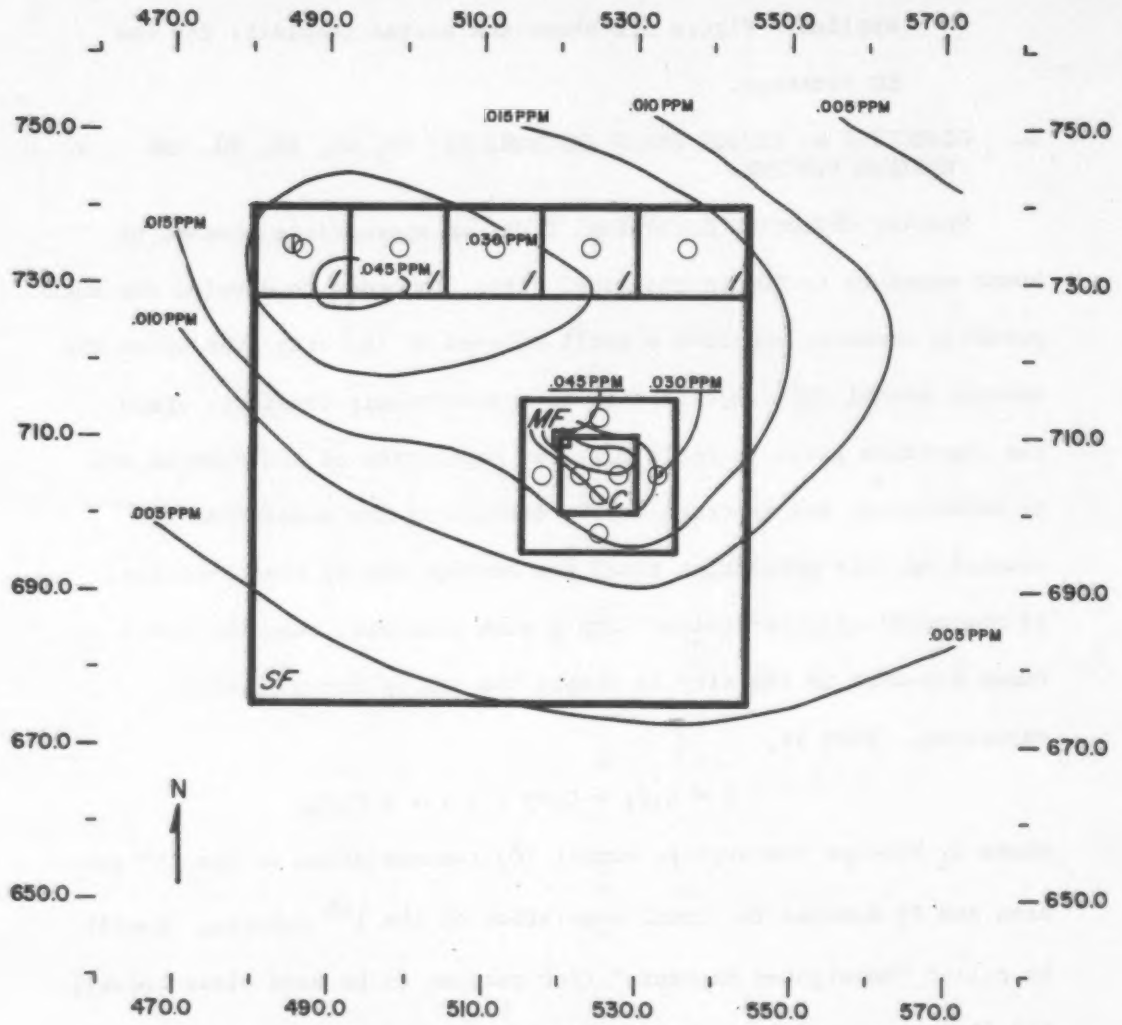
CONCENTRATIONS AT SIXTEEN HIGHEST POINTS
AFTER REDUCTION TO 0.050 ppm or LESS

COORDINATES		POWER PLANTS			OTHER SOURCES				TOTAL ALL SOURCES
HORIZ.	VERT.	UPTN.	DNTN.	TOTAL	IND.	COMM.	M.F.	TOTAL	
470.0	750.0	0.022	0.001	0.023	0.003	N	N	0.003	0.026
490.0	750.0	.014	.001	.015	.006	N	N	.006	.021
490.0	730.0	.035	.001	.036	.013	0.001	N	.014	.050
510.0	750.0	.007	.001	.008	.008	.001	N	.009	.017
510.0	730.0	.018	.003	.021	.018	.001	N	.019	.040
510.0	710.0	.009	.004	.013	.003	.002	N	.005	.018
530.0	730.0	.009	.001	.010	.014	.001	N	.015	.025
530.0	710.0	.007	.010	.017	.003	.005	0.002	.010	.027
517.5	712.5	.008	.026	.034	.004	.005	.001	.010	.044
517.5	697.5	.005	.003	.008	.002	.001	.001	.004	.012
722.5	707.5	.007	.017	.024	.003	.019	.001	.023	.047
722.5	702.5	.006	.007	.013	.002	.010	.002	.014	.027
527.5	707.5	.006	.014	.020	.003	.022	.002	.027	.047
527.5	702.5	.005	.007	.012	.002	.020	.001	.023	.035
532.5	712.5	.007	.005	.012	.004	.002	.001	.007	.019
532.5	697.5	.004	.004	.008	.002	.005	.001	.008	.016

FIGURE 5.6

AVERAGE ANNUAL SULFUR DIOXIDE CONCENTRATIONS (PPM)

ALL SOURCES,
LC REDUCTION OF ALL CONCENTRATIONS TO LESS THAN 0.050 PPM



EQUALS 1 MILE
UPTOWN POWER PLANT WITH 200 METER STACK
DOWNTOWN POWER PLANT
ALL OTHER SOURCES

/ INDUSTRIAL
MF MULTI-FAMILY
C COMMERCIAL
SF SINGLE FAMILY

reduction in emissions from each source (the amount by which all concentrations due to that source are to be reduced). Table 5.10 shows the concentrations at the locations listed on table 5.6 after reductions have been applied. Figure 5.6 shows the abated isopleths for the LC strategy.

D. OBJECTIVE 4: REDUCE HUMAN EXPOSURE BY 20, 40, 60, 80, AND MAXIMUM PERCENT.

Meeting Objective 4 requires first an appropriate measure of human exposure to SO_2 in the model city. In order to develop one such possible measure, consider a small subarea of the city over which the average annual SO_2 concentration is approximately constant. From the densities given in table 3.1, the population of the subarea can be calculated, and exposure may be defined in the subarea as the product of this population times the average annual concentration. If the model city is divided into n such subareas, then the total human exposure in the city is simply the sum of the n subarea exposures. That is,

$$E = C_1P_1 + C_2P_2 + \cdots + C_nP_n,$$

where C_1 denotes the average annual SO_2 concentration in the 1^{th} subarea and P_1 denotes the total population of the 1^{th} subarea. E will be called "unweighted exposure" (for reasons to be made clear below), and it is measured in units of people times ppm, hereafter abbreviated p-ppm. In physical reality, of course, concentrations vary continuously over the surface of the city (i.e., concentration is not really constant

over any subarea, however small). Thus E is a discrete approximation to the number of "p-ppm" under the continuous contour of concentrations covering the city. This approximation can be made as accurate as desired by dividing the city into a sufficiently large number of subareas (i.e., making the subareas sufficiently small). Since a concentration reading is required for each subarea, a receptor point must be predesignated within each subarea in the met model.

1. Equal-Proportional Strategy

   For actual computation, the model city has been divided into twenty-three subareas, each of which is roughly centered about a receptor point. The first column of table 5.11 shows the total "unweighted" human exposure in the model city before abatement, and the contribution of each emitting source to that total. The remainder of table 5.11 shows the costs associated with reducing this total unweighted exposure by 20, 40, 60, 80, and 83 percent with an EP strategy.

2. Least-Cost Strategy

   Using information on the unit costs of the various technologies available to the different emitting sources, LC strategies have been developed for effecting these same reductions in unweighted human exposure. Table 5.12 shows the control techniques used to attain each level of reduction, the costs associated with each level of reduction, and the exposure contributions of the various emitting sources at each level of reduction.

TABLE 5.11

COST OF REDUCING UNWEIGHTED EXPOSURE
BY EQUAL-PROPORTIONAL STRATEGY

SOURCE	AVERAGE ANNUAL EXPOSURE BEFORE REDUCTION		20% REDUCTION			40% REDUCTION			60% REDUCTION			80% REDUCTION			MAXIMUM REDUCTION (83%)		
	P-PPM	%	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)
Power plants:																	
Uptown	36,104	21.5	28,880	Fuel sub.	$ 1,641	21,660	High stack	$ 230	14,440	High stack, fuel sub.	$ 3,184	7,220	High stack, stack clean	$ 6,280	412	High stack, stack clean and fuel sub.	$ 17,157
Downtown	69,279	41.2	55,400	Fuel sub.	824	41,500	Fuel sub.	1,648	27,640	Stack clean	4,000	13,820	Stack clean	4,920	2,760	Stack clean	9,220
TOTAL	105,383	62.7	84,280		2,465	63,160		1,878	42,080		7,184	21,040		11,200	3,172		26,377
Other sources:																	
Industrial	29,547	17.6	23,600	Fuel sub.	813	17,700	Fuel sub.	2,145	11,800	Fuel sub.	4,273	5,900	Fuel sub.	5,145	11,800	Fuel sub.	5,145
Commercial	30,404	18.0	24,400	" "	240	18,300	" "	684	12,200	" "	1,188	6,100	" "	1,620	12,304	" "	1,620
Multi-family	2,750	1.6	2,200	" "	24	1,650	" "	48	1,100	" "	96	550	" "	120	900	" "	120
TOTAL	62,701	37.3	50,200		1,077	37,650		2,877	25,100		5,359	12,550		6,885	25,004		6,885
GRAND TOTAL	168,084	100	134,480		$ 3,542	100,810		$ 4,755	67,180		$ 12,743	33,590		$18,085	28,176		$ 33,262

TABLE 5.12
COST OF REDUCING UNWEIGHTED EXPOSURE
BY LEAST-COST STRATEGY

	AVERAGE ANNUAL EXPOSURE BEFORE REDUCTION		20% REDUCTION			40% REDUCTION			60% REDUCTION			80% REDUCTION			MAXIMUM REDUCTION (83%)		
	P-PPM	%	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)	AVERAGE ANNUAL EXPOSURE P-PPM	METHOD	ESTIMATED ANNUAL COST (000)
Power plants:																	
Uptown	36,104	21.5	21,700	High stack	$ 230	21,700	High stack	$ 230	21,700	High stack	$ 230	2,200	High stack, stack clean.	$ 7,020	412	High stack, stack clean, and fuel sub.	$17,157
Downtown	69,279	41.3	69,279	NC		36,579	Fuel sub.	3,040	6,928	Stack clean.	5,130	6,928	Stack clean	5,130	2,760	Stack clean	9,220
TOTAL	105,383	62.8	90,979		230	58,279		3,270	28,628		5,360	9,128		12,150	3,172		26,377
Other sources:																	
Industrial	29,547	17.6	29,547	NC		29,579	NC		28,400	Fuel sub.	157	11,800	Fuel sub.	4,280	11,800	Fuel sub.	5,145
Commercial	30,404	18.0	12,304	Fuel sub.	1,170	12,304	Fuel sub.	1,170	12,304	" "	1,170	12,304	" "	1,170	12,304	" "	1,620
Multi-family	2,750	1.6	1,740	" "	41	900	" "	126	900	" "	126	900	" "	126	900	" "	120
TOTAL	62,701	37.2	43,591		1,211	42,751		1,296	41,604		1,453	25,004		5,576	25,004		6,885
GRAND TOTAL	168,084	100	134,570		$1,441	101,030		$4,566	70,232		$6,813	34,132		$17,726	28,176		$33,262

3. Differences in Costs of Strategies

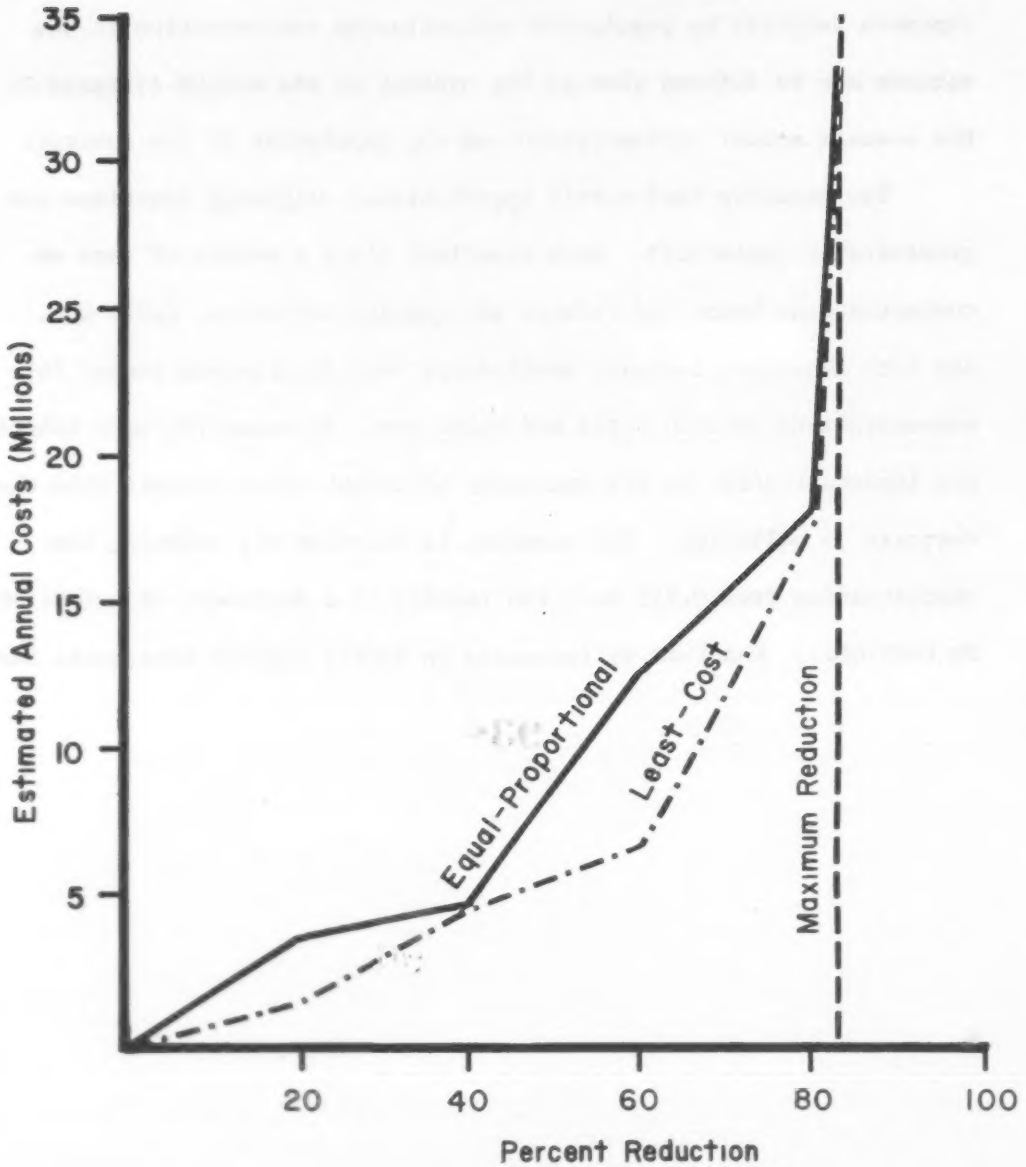
Figure 5.7 shows the cost differences between the EP and the LC strategies for attaining 20, 40, 60, 80, and 83 percent reductions in unweighted human exposure. The largest difference in cost between the two strategies is $5,930,000, which occurs at 60-percent reduction, where the EP strategy costs $12,743,000 and the LC strategy $6,813,000. As in meeting other abatement objectives (e.g., reduce emissions, reduce highest concentration), the two strategies give identical costs only for the maximum attainable reduction, for which all available abatement technologies are employed. For this particular objective, the two strategies yield similar costs for 40 and 80-percent reductions, but the least-cost strategy is much less expensive for 20-percent ($1,441,000) and 60-percent ($6,813,000) reductions.

4. Human Exposure Weighted by Population and Concentration

It should be emphasized that the measure of human exposure developed above is only one of many possible definitions. In this measure, all people are treated equally. Each subarea of the city is distinguished in this criterion by the number of people exposed in the area and the concentrations to which they are exposed. For the purposes of demonstration again, consider a small subarea of the model city over which the average annual SO_2 concentration is essentially constant and has a value C=0.050 ppm. Suppose that the population of the subarea is 1,000 and that a system of weights has been worked out which reflects the fact that up to a point higher levels of pollution are more harmful than lower levels and on that basis assigns a weight of 16 to the concentration of 0.050 ppm. That is, one person exposed to a concentration

FIGURE 5.7

COMPARISON OF ESTIMATED ANNUAL COSTS OF REDUCING UNWEIGHTED HUMAN EXPOSURE— EQUAL-PROPORTIONAL AND LEAST-COST STRATEGIES



of 0.050 ppm. is deemed to be 16 units more important than one person exposed to some base-level or benchmark concentration. The human exposure weighted by population and pollution concentration in the subarea may be defined then as the product of the weight assigned to the average annual concentration and the population of the subarea.

Two possible (and purely hypothetical) weighting functions are presented in table 5.13. Both functions place a weight of zero on concentrations below the Federal air quality criterion, 0.015 ppm, and both functions increase nonlinearly (but in discrete steps) for concentrations between 0.015 and 0.250 ppm. In examining both functions the important point is the decrement of weight which results from the decrease in pollution. For example, in Function #1, reducing the concentration from 0.255 to 0.240 results in a decrement of weight of 50 (460-410). Function #1 increases in fairly regular increments for

Table 5.13
HYPOTHETICAL WEIGHTING FUNCTIONS

Function #1	Weights of Concentration Function #1 $W(C)_1$	$\Delta W(C)_1$	Weights of Concentration Function #2 $W(C)_2$	$\Delta W(C)_2$
0-0.014	0		0	
0.015-0.029	2	2	2	2
0.030-0.044	7	5	7	5
0.045-0.059	16	9	16	9
0.060-0.074	27	11	27	11
0.075-0.089	40	13	40	13
0.090-0.104	60	20	60	20
0.105-0.119	80	20	80	20
0.120-0.134	100	20	100	20
0.135-0.149	130	30	130	30
0.150-0.164	160	30	160	30
0.165-0.179	190	30	190	30
0.180-0.194	230	40	230	40
0.195-0.209	270	40	270	40
0.210-0.224	310	40	310	40
0.225-0.239	360	50	360	50
0.240-0.254	410	50	2800	2440
0.255-0.269	460	50	2970	170
0.270-0.284	510	50	3150	180
0.285-0.299	570	60	3340	190
etc.				

concentrations above .240, whereas Function #2 places a very high weight on concentrations above 0.240. Function #2 might provide an appropriate measure of effective exposure if 0.240 ppm. were judged to be the lowest SO_2 concentration at which abatement is obligatory. (The particular value of 0.240 ppm. has been chosen for demonstration purposes only and is not to be taken as a recommendation.)

The abatement problem is to allocate the expenditure of funds so that the greatest decrement in weighted exposure is achieved for a given level of expenditure. Or alternatively, if it is decided to

reduce human exposure by a certain amount, then the decrement "purchased" with each successive dollar should be as large as possible until the desired level is reached.

For example, using Function #2, there are three subareas of the model city with initial concentrations (i.e., before abatement) above 0.240 ppm. That is, there are three subareas initially in the "penalty category" with a weight of at least 2800. A very inexpensive control procedure may bring these concentrations below 0.240 ppm. and hence effect a reduction in weighted human exposure. Table 5.14 also shows that widely different results can be obtained using the two different weighting functions.

Table 5.14

	Function #1		Function #2	
C	W(C)	Decrement of Exposure Gained Per Capita	W(C)	Decrement of Exposure Gained Per Capita
.299-.285	570		3340	
.284-.270	510	60	3150	190
.269-.255	460	50	2970	180
.254-.240	410	50	2800	170
TOTALS		160		540

For example, when using Function #1 $1,648,000 purchases a decrement of weighted human exposure roughly one-third of the amount purchased when Function #2 is used as the weight.

5. Broader Implications of Weighting Functions

The pollution control objectives posed in Chapter IV and evaluated in this Chapter have been presented in increasing order of sophistication. Ultimately, concern does not rest upon emissions, nor upon the concentrations

Table 5.15
SAMPLE CALCULATIONS OF THE COST OF REDUCING WEIGHTED HUMAN EXPOSURE VERSUS THE COST OF REDUCING UNWEIGHTED HUMAN EXPOSURE

I. To reduce human exposure:

The least cost for a 20% reduction is. . . .	$ 1,441,100/yr.
The least cost for a 40% reduction is. . . .	4,766,000/yr.
The least cost for an 80% reduction is . . .	17,726,000/yr.

II. To reduce exposure weight by intensity of concentration using Function #1:

There exists a strategy which gives a 40% reduction for	$ 1,548,000/yr.

III. To reduce exposure weighted by intensity of concentration using weighting Function #2:

There exists a strategy which gives a 20% reduction for	$ 72,000/yr.
There exists a strategy which gives an 80% reduction for	$ 1,548,000/yr.

caused by emissions, nor upon the exposures caused by concentrations. Rather, the final quantity of concern is the damage or discomfort resulting from such exposures, Thus, any attempt to weight exposures appropriately is in actuality an attempt to develop an "effective exposure" or "damage function." If such a function is well constructured, and if it shows that a very small reduction in emissions can yield a very large reduction in "damage," then the appropriate conclusion is that very powerful abatement procedures are available. Certainly no doubt is cast upon the validity of the weighting function

because of this propitious result.

Finally, it seems likely that the concept of a weighting function as "damage function" can be extended to provide a powerful tool in analyzing the simultaneous effects of several pollutants. To demonstrate this, consider again a small subarea, over which the average annual concentrations of each of two different pollutants are approximately constant. Suppose that the two pollutants act independently. Then the "damage" in the subarea might be expressed by the relationship

$$D = C_1 W_1(C_1) P + C_2 W_2(C_2) P,$$

where D is the damage in the subarea, C_1 and C_2 are the average annual concentrations of pollutants 1 and 2 respectively, P is the population of the subarea, and $W_1(C_1)$ and $W_2(C_2)$ are the weighting functions for pollutants 1 and 2 respectively. Again the total damage for the city would presumably be the sum of the damages for all such subareas. Note that $W_1(C)$ and $W_2(C)$ must be scaled so as to reflect the comparative destructiveness of the two pollutants. If the two pollutants do not act independently, it seems likely that their interaction can be accounted for by including a cross-product term in the damage expression. However, it might be difficult to develop appropriate weighting functions for such terms.

E. EFFECT OF TIME-PHASING ON COSTS

In the foregoing discussions of abatement strategies, an assumption is implied that the emission control techniques in an abatement combination are all applied concurrently. If, in fact, installation of controls is time-phased, there is a possibility of lower costs (given stable price levels) because research and development may produce cheaper and more effective devices. Lower costs may be offset, however, by prolonging damage to people, materials, and vegetation, which could have been more greatly reduced by concurrent controls. Time-phasing greatly complicates the problem of analyzing abatement strategies and costs, and is therefore not examined quantitatively here. Further mention of time-phasing is made in Chapter VI.

F. EFFECT OF POWER PLANT RELOCATION ON COSTS

As mentioned in Chapter III (H.5), relocation of power plants was not considered in combination with other SO_2 emission control techniques available to meet the abatement objectives because of the great uncertainties in the relocation costs. However, as a separate abatement consideration, figure 3.19 shows the isopleths of the average annual SO_2 concentrations for the model city after relocation of the power plants to grid coordinates H-650.0, V-790.0 (not shown), which is about twenty-five miles from the northeast corner of the model city. The average concentration taken over all 44 receptor points after relocation is only 1.7 percent of the average concentration before relocation. Thus, if the assumed costs

of relocation are realistic (and there is little confidence that they are), a higher maximum reduction in emissions and concentrations can be effected more cheaply than indicated in tables 5.1, 5.2, 5.4, and 5.5. Also, the cost of achieving Objective 3 could be significantly reduced, as could the cost of achieving Objective 4.

VI. CONSIDERATIONS IN REAL APPLICATIONS

Demonstration of a simulation approach to a cost-effectiveness analysis of air pollution abatement strategies implies that simulation can accommodate the significant realities of actual urban air pollution situations. The purpose of this chapter is to examine briefly the principal factors which should be considered in real applications of a simulation approach.

There are a number of purposes for which the simulation of air pollution can be employed. Example purposes will be posed here so that factors important to real situations can be discussed in meaningful contexts:

1. Development of detailed decision aids for implementation of air pollution abatement programs by regional, State, or local authorities.
2. Evaluating, for different clean air goals, the cost-effectiveness advantages of proposed emission control techniques.
3. Allocation of Federal resources, including economic incentives for private abatement, on a cost-effectiveness basis.

Applicable to all three purposes are the following factors, which have already been discussed in Chapters II and III and do not require further comment here:

- The common pollutants and their principal interactions, e.g., CO, odors, hydrocarbons, NO_x, SO_x, particulates, and photochemical smog.
- Location and source strength of pollution, e.g., combustion sources, industrial processes, incinerators, transportation, and future growth.

port of pollutants.

- Complete range of emission control options for each pollutant for reduction of annual average and for episode situations (see Chapter III, Section H).

1. Decision Aids for Abatement Authorities

In addition to implementing Federal clean air directives, local, State, or regional abatement authorities may have the responsibility for pursuing abatement objectives which reflect not only utilitarian values, but also the prevailing political realities of the area. Moreover, it is likely that proposed strategies for pollution abatement which are "best" on an objective cost-effectiveness basis may be unacceptable politically. The desire of the local abatement authority, then, may not be only for optimal strategies, but also for evaluating the effect of a range of nonoptimal strategies. In this way, political decisions can be guided, at least partly, by indicating those abatement strategies which are deemed to be reasonable compromises.

Therefore, in addition to producing complex schedules of emission controls for the various polluting activities which meet preferred objectives optimally, it would also be useful for the abatement authority to have brief summaries of the degree to which certain abatement objectives and strategies deviate from those preferred. It would be important to be able to present concisely the penalties implied by nonpreferred choices in terms of damage effects, additional costs to achieve objectives, and inequities of cost due to differing economies of scale among the polluting sources. Computer-assisted simulation has both the flexibility and the speed to provide "edited output" to satisfy such needs.

2. Evaluating Emission Control Techniques

For Federal, State, and local governments, and for public and private research groups, simulation can provide a rapid means of evaluating the cost-performance advantages of competing techniques for emission control based on the specific abatement objectives being pursued in an area.

For example, if a locale is pursuing an objective which requires reduction of pollutant concentrations or damage-effects, it is possible that, because of the meteorological peculiarities of the area, the biggest emitter of pollutants contributes a disproportionately small amount to local concentrations and damage. Thus, one emission control device may be "best" when concentration or damage reduction is the criterion, and another device when emission reduction is the criterion. The different results and costs shown in Chapter V for objectives with different effect criteria indicate that the problem is at least not trivial. Simulation can provide a direct means of determining which degree of emission control (and, hence, which control devices or actions) is both feasible and economically preferred.

3. Allocation of Federal Resources

At the Federal level, simulation can provide a powerful means of determining the common and uncommon characteristics of air pollution situations within political units and within regions, so that: (a) funds can be requested and allocated equitably among competing air pollution programs on a cost-effectiveness basis and (b) the equity of extant and proposed clean air legislation can be assessed.

Cost-effectiveness analysis seeks the optimum allocation of program funds, that is, the mix of programs which will maximize the net benefits per program dollar. Ideally, public air pollution programs are economically self-liquidating because there is a direct feedback of Federal revenues from the longer productive life of people previously hazarded by pollution, and an indirect feedback from increased economic activity.* These feedbacks require dollar measurement of pollution damage to people, animals, materials, and vegetation; and determination of the impact on these feedbacks of the time-phasing of abatement actions. Such damage functions do not yet exist for the various pollutants. Without them, air quality criteria may be stipulated separately for people, animals, materials, and vegetation on the basis of the best scientific evidence of physical damage at various pollutant levels. These criteria would then be demand parameters and cost-effectiveness analysis would seek an allocation of funds which maximizes the reduction in damage-producing exposure for each exposed class, as was done in Chapter V for people in the model city.

Simulation can be a direct means of assessing the equity of clean air legislation, including incentives for abatement through tax adjustments or through emission charges. The contributions of different kinds of industries and activities to total emissions of a pollutant, to ground-level concentrations, to the damage caused to the

---

* Raphael, D.L. and Enscore, E.E., Jr., The Direct and Indirect Economic Impact of Regional Air Pollution, paper #67-42, presented at the 60th Annual Meeting of the Air Pollution Control Association, June 11-16, 1967, Cleveland, Ohio.
Economic activity is one dimension of human life. The avoidance of pain, disability and premature death are not fully measured by inputting productivity. Benefits apart from production must be examined when making program decisions, as must political as well as economics costs.

different exposed classes, and to delineation of the most probable abatement schemes, can be rapidly developed for a city, as has been demonstrated. By simulating a variety of cities, the nationwide contribution of the different industries and activities to air pollution, and the methods to be used for control, can be aggregated. By taking into account economies of scale among the industries in relation to the damage they do, a more economically sound basis can be developed for determining the proper mix of tax incentives and emission charges. The relative demand for resources, on a nationwide basis, for urban, rural, and regional air pollution abatement can also be assessed by scaling the simulation models employed and using large-scale meteorological models.

- - - - - - - - - - - - -

The foregoing discussion has attempted to indicate the range of application and flexibility of the simulation approach to the economic analysis of air pollution abatement given certain abatement objectives. An important remaining question is why an area would choose to pursue something other than the objective which maximizes the long-term net effectiveness on a cost-effectiveness basis. There are at least five possible reasons. First, effectiveness data may be unavailable or available only after considerable delay. Second, effectiveness data may be differently interpreted, resulting in heavier emphasis on the avoidance of peaks and disasters rather than on achieving improvement in the average long-term air quality. Third, short-run solutions involving less administrative difficulty may not diverge significantly from the optimum objective for the short run. Fourth, the weight

given to air pollution control within a firm may make certain routes more attractive. For example, public utilities can gain an immediate rate increase for increased variable costs, but must wait for a review of their cost structure to recoup capital expenditures for air pollution control. Fifth, an objective may be chosen out of political compromise.

It should be clear from this study that computer-assisted simulation provides a highly adaptable means either for comparing abatement strategies designed to achieve a clean air objective or for comparing objectives given alternative strategies.

VII. CONCLUSIONS AND RECOMMENDATIONS

Set forth below are the salient conclusions and recommendations of this study. It is to be emphasized that results of the simulation demonstrated in Chapters III, IV, and V do not support any general conclusions on how SO_2 or any other pollutant can be controlled, and therefore, do not provide an adequate basis for recommending air pollution control policy.

A. CONCLUSIONS

1. Simulation is a vital tool for effective air resource management. Even considering only SO_x abatement, the many possible clean air objectives, the variety of sources and their distribution, future community growth, and the wide variety of available control methods, make it impossible to analyze the situation adequately and plan optimum control strategy without the use of computer-assisted simulation methods.
2. A variety of clean air objectives can be stated in air pollution situations and the term "abatement" can have many meanings and be achieved by a number of alternative strategies.
3. The costs and effectiveness of achieving different clean air objectives can vary greatly in any particular pollution situation.
4. It is not possible to define an optimum SO_2 control plan that is generally applicable; the factors are too complex and vary significantly among cities. It is possible, however, to formulate a general model of the pertinent interrelationships that then can be used with local data to provide analyses

B. RECOMMENDATIONS

1. The development of a general simulation model for SO_2 pollution and its control should be undertaken as soon as possible. Since SO_2 is only one of many air pollution problems needing analysis, the structure of its analytical model should be compatible with a larger more general air pollution system. The simplifying assumptions of the model were noted previously. The next steps in complexity require simulation without these constraints. That is, among other things, future models should move away from annual average to include episode situations and daily average concentrations. Noncombustion sources should be added to the model. More than one pollutant should be analyzed, and the interactions of pollutants should be included. The cleansing ability of the air and alteration of pollutants through atmospheric reactions should be added variables.

2. The least cost solution may often be difficult to implement. Studies should be undertaken on the institutional mechanisms that may be required to administer least cost solutions.

3. Increased emphasis should be given to the collection of information for major urban areas that will stimulate use of simulation and allow rapid application of general models that are developed. These include information on:

(a) the incremental effects of SO_x suitable for development of damage functions for all important receptors;

(b) the effectiveness and cost of incremental control for all possible control options for different parts of the country, both for current technology and estimated future capabilities; effectiveness of SO_2 control techniques on other pollutants, especially particulates should be included;

APPENDIX A. METEOROLOGICAL DIFFUSION MODEL

The meteorological diffusion model used in this study calculates the most probable average ground-level pollutant concentration (in parts per million) produced by a single point source at one or more receptor points. The model is based on the generalized Gaussian diffusion equation[1]/ [2]/, which follows, and was applied using a program written for an IBM 1130 computer.

$$C = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\tfrac{1}{2}\left(\frac{Y^2}{\sigma_y^2} + \frac{H^2}{\sigma_z^2}\right)\right]$$

where:

C = pollutant concentration, grams per cubic meter

Q = pollutant emission rate, grams per second

$\bar{u}$ = wind speed, meters per second

H = effective height of source, meters

y = horizontal distance from plume centerline, meters

σ_y = standard deviation of the distribution of pollutant concentrations in the horizontal direction, meters

σ_z = standard deviation of the distribution of pollutant concentration in the vertical direction, meters

Figure A.1 shows pictorially the plume resulting from emissions from a single source, and the above equation describes the concentration as following a normal distribution from the plume centerline in both the horizontal and the vertical directions.

1/ Hilsmeier, W. F., and Gifford, F. A., Jr. Graphs for Estimating Atmospheric Diffusion, ORO-545 Atomic Energy Commission. Oak Ridge, Tennessee. 1962. 10 pp.

2/ Gifford, F. A., Jr. Atmospheric Dispersion Calculations Using the Generalized Gaussian Plume Model. Nuclear Safety, 4:47-51. 1961.

(c) detailed emission data for SO_2 for important urban areas;

(d) quantitative relationships between SO_2 and other air pollutants, including particulates and photochemical smog; and

(e) meteorological information for important urban areas suitable for development of sophisticated dispersion models.

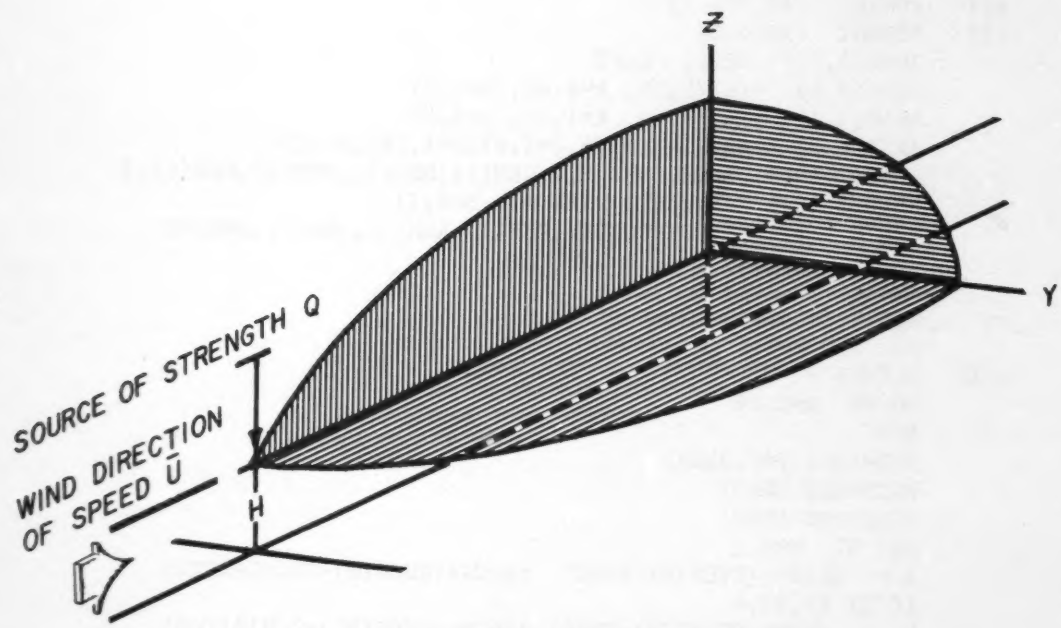
TABLE A.1

DIFFUSION MODEL PROGRAM LISTING (FORTRAN IV)

```
      DIMENSION SC(5,16,6),AZ(6.5),BZ(6,5),REM(4)
      DIMENSION RHOR(50), RVER(50).VAL(50)
    1 FORMAT  (4X,6F11.5)
    2 FORMAT  (7X,6F7.5)
  101 FORMAT (1H1/1HO,3X,6HSOURCE.  25X.2F8.1,8X,4A6)
  102 FORMAT  (1HO,3X,27HEMISSION  RATE IN GRAMS/SEC.,F10.2/1HO)
  103 FORMAT  (1HO,3X,22HSTACK  HEIGHT  IN METERS, 5X,F10.2)
  104 FORMAT  (1HO,22X,26HCOORDINATES   VALUE IN PPM)
  105 FORMAT  (1HO,20X,F6. 1,F8.1,E14.5)
  106 FORMAT  (1X,2F4.1,F5.2,F6.2,4A6,12)
  107 FORMAT  (1X,2F4.1)
   73 FORMAT  (2F10.5)
      READ(2,73)  GRID,  ALWT
      READ(2,1)  ((AZ(K,L), K=1,6), L=1.5)
      READ(2,1)  ((BZ(K,L), K=1,6), L=1,5)
      READ(2,2)   (((SC(M,N,J),J=1,6),N=1,16),M-1,5)
      READ(2,106)  SHOR,SVER,H,Q,REM(1),REM(2),REM(3),REM(4),I
      READ(2,107)  (RHOR(M),RVER(M), M=1,I)
      WRITE  (3,101)  SHOR,SVER,REM(1),REM(2),REM(3),REM(4)
      WRITE  (3,102) Q
      WRITE  (3,103) H
      WRITE  (3,104)
      DO  110 M=1,I
  110 VAL(M) =  0.0
      DO 96  N=1.16
      B=N
      RAD=(B-1.)*(.3927)
      BSIN=SIN (RAD)
      BCOS=COS (RAD)
      DO  97  M=1,I
      X =  GRID*((RVER(M)-SVER)  *BCOS+(RHOR(M)-SHOR)*BSIN)
      IF(X) 97,97,4
    4 Y  =  GRID*((RVER(M)-SVER) *BSIN-(RHOR(M)-SHOR)*BCOS)
      SIGY =  .157 * X
      IF  (SIGY-5000.)  36,36,35
   35 SIGY=5000.
   36 ARG2 = (-.5*Y*Y)/(SIGY*SIGY)
      IF  (ABS (ARG2) - 60.)32,97,97
   32 STO = EXP (ARG2)
      DO 98  L=1,5
      DO 99  J=1,6
      F  = SC(L,N,J)
      IF (F) 99,99,10
```

FIGURE A.I

PLUME FROM SINGLE SOURCE



The values of σ_y and σ_z depend upon the atmospheric stability and the source-to-receptor distance measured along the centerline. The important meteorological factors that affect concentrations at particular points are wind speed, wind direction, and stability class. Over any time period, these occur in various combinations, and they were taken into account in the diffusion model by using a weighting factor that indicates the proportion of time in which each combination occurs during the prescribed time period. The wind-speed categories chosen are (in miles per hour) 1 to 3, 4 to 7, 8 to 12, 13 to 18, 19 to 24, and in excess of 25. A total of 16 wind directions were used, spaced around the compass at angles of 22½°. Five stability classes were selected; the first four correspond to Pasquill's classes A to D, 3/ while the fifth represents Pasquill's categories E and F grouped together. Calms were distributed in the lowest wind-speed category for the five stability classes and 16 wind directions in the same proportion as indicated by observed data. The weighting factors representing the frequency of occurrence of the various meteorological combinations were stored in the program in a three-dimensional array of 480 cells (6 x 16 x 5 units).

The meteorological data used were those recorded at the St. Louis airport for the period extending from December 1, 1964, to February 28, 1965. These data were entered into the array, which serves in the program as a "numerical wind rose."

3/ Pasquill, F. The Estimation of the Dispersion of Windborne Material. Meteorol. Mag. 90:33-49. 1961

```
 10    GO  TO  (14,15,16,17,18,19), J
 14    WS  =  .67056
       GO  TO  20
 15    WS  =  2.45872
       GO  TO  20
 16    WS = 4.4704
       GO  TO 20
 17    WS  =  6.92912
       GO  TO  20
 18    WS  = 9.61136
       GO  TO  20
 19    WS  =  12.51712
 20    T  =  X / WS
       IF  (T-300.)  21,21,22
 21    K=1
       GO TO 31
 22    IF  (T-1000.)  23,23,24
 23    K=2
       GO TO  31
 24    IF  (T-3000.) 25,25,26
 25    K=3
       GO TO 31
 26    IF (T-10000.) 27,27,28
 27    K=4
       GO TO 31
 28    IF  (T-30000.) 29,29,30
 29    K=5
       GO TO 31
 30    K=6
 31    SIGZ=AZ(K,L)*T**BZ(K,L)
       IF (SIGZ-5000.) 34,34,33
 33    SIGZ=5000.
 34    ARG1 = (-.5*H*H)/(SIGZ*SIGZ)
       IF  (ABS (ARG1) - 60.)37,99,99
 37    C = ((F*Q)/(3.14159*WS*SIGY*SIGZ))     *EXP (ARG1) * STO
       VAL(M) = VAL(M) + C
 99    CONTINUE
 98    CONTINUE
 97    CONTINUE
 96    CONTINUE
       DO 115 M=1,I
       VAL (M) = VAL(M) * ALWT
115    WRITE(3,105) RHOR(M),RVER(M),VAL(M)
       CALL EXIT
       END
```

Additional input consists of the grid coordinates of the emission source and all receptor points.

Figure A.2 presents a generalized layout of the program logic; table A.1 gives a listing of the program in FORTRAN IV language.

The factors ALWT and GRID are conversion constants. ALWT converts the grams-per-cubic-meter output of the basic equation into parts per million. The factor varies by the molecular weight of the pollutant involved. A list of some of these factors for common pollutants follows:

POLLUTANT	ALWT
SO_2	375.66
NO	801.06
NO_2	522.50
H_2S	705.40
CO	858.26
CO_2	546.23
NH_3	1411.63
Cl_2	339.02
HCl	659.17
HF	1201.39

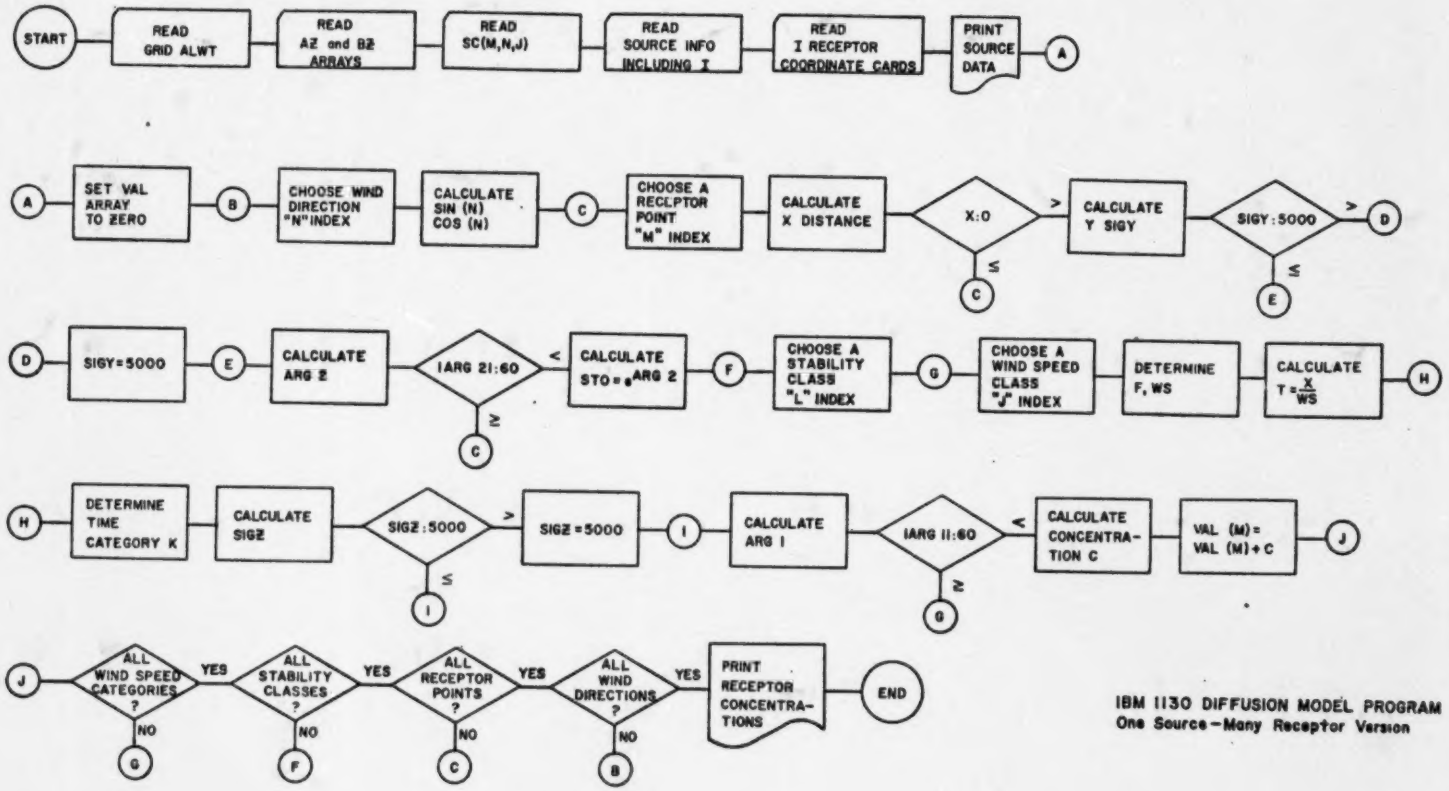
The factor GRID is for converting into meters the units of the grid coordinates on which the source and receptors are located. One unit of a grid coordinate system times GRID equals a certain number of meters.

Both constants are assumed for conditions of 20°C and at one atmosphere of pressure.

For a discussion of the validity of using a Gaussian diffusion model in estimating pollution concentrations, the reader is referred to:

Miller, M.E. and Holzworth, G.C., An Atmospheric Diffusion Model for Metropolitan Areas, Journal of the Air Pollution Control Association, Vol. 17, No. 5, Jan. 1967.

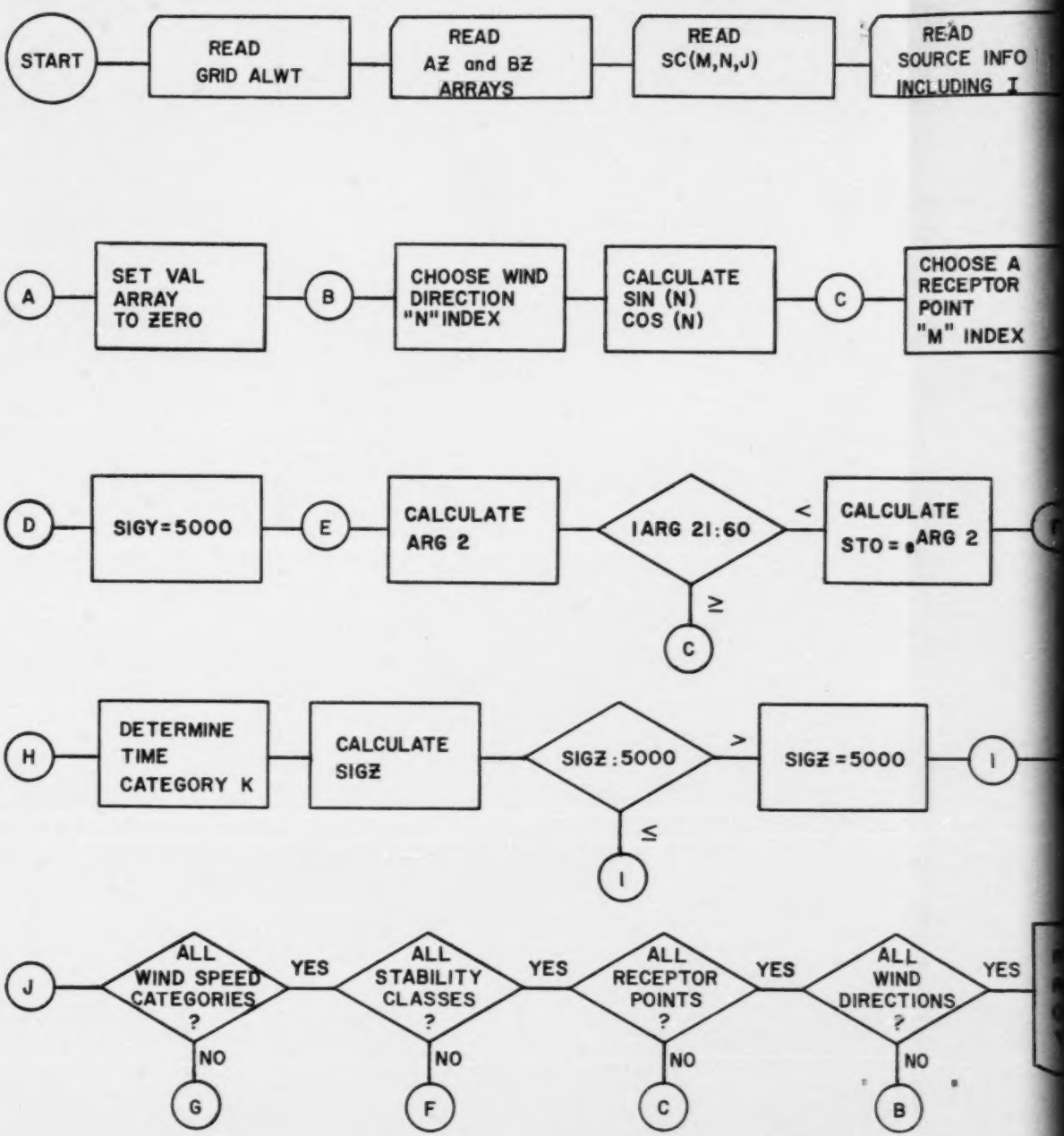
FIGURE A.2
DIFFUSION MODEL PROGRAM LOGIC

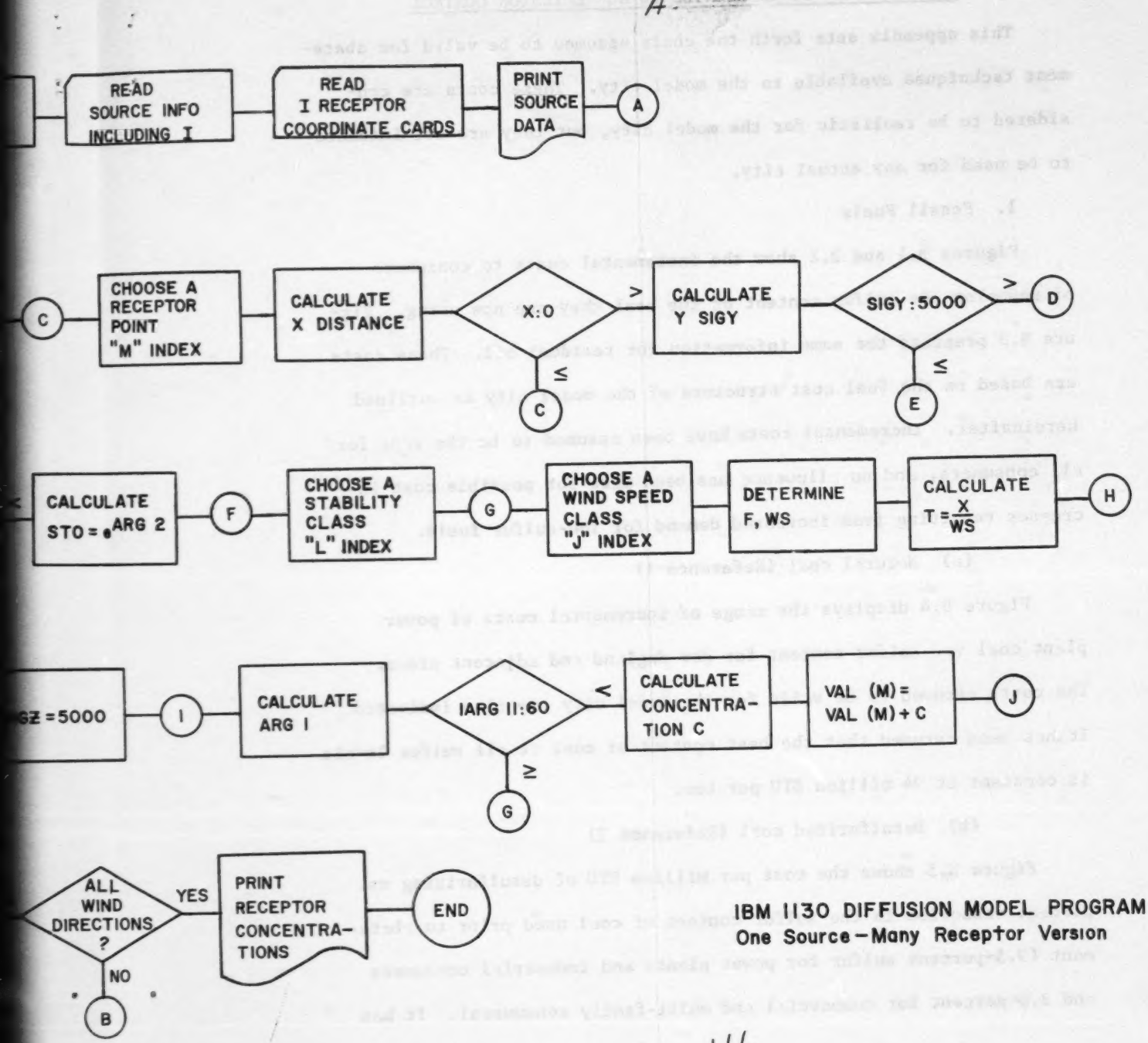


IBM 1130 DIFFUSION MODEL PROGRAM
One Source—Many Receptor Version

FIGURE A.2

DIFFUSION MODEL PROGRAM LOGIC





IBM 1130 DIFFUSION MODEL PROGRAM
One Source—Many Receptor Version

B

APPENDIX B. COSTS RELATED TO SO_2 EMISSION CONTROL

This appendix sets forth the costs assumed to be valid for abatement techniques available to the model city. These costs are considered to be realistic for the model city, but they are not intended to be used for any actual city.

1. Fossil Fuels

Figures B.1 and B.2 show the incremental costs to consumers of reducing the sulfur content of the coal they are now using. Figure B.3 presents the same information for residual oil. These costs are based on the fuel cost structure of the model city as outlined hereinafter. Incremental costs have been assumed to be the same for all consumers, and no allowance has been made for possible cost increases resulting from increased demand for low-sulfur fuels.

(a) Natural coal (Reference 1)

Figure B.4 displays the range of incremental costs of power plant coal vs. sulfur content for New England and adjacent areas. The costs assumed to be valid for the model city are also indicated. It has been assumed that the heat content of coal at all sulfur levels is constant at 24 million BTU per ton.

(b) Desulfurized coal (Reference 2)

Figure B.5 shows the cost per million BTU of desulfurizing vs. percent reduction in the sulfur content of coal used prior to abatement (2.5-percent sulfur for power plants and industrial consumers and 3.0-percent for commercial and multi-family consumers). It has

TABLE B.1

ESTIMATED ANNUAL COST OF STACK CLEANING

Downtown plant, 1,200 megawatts--Cost $12,000,000

	Percent SO_2 Removal				
	20	40	60	80	90
	(hundred thousands)				
Variable costs	920	1,620	2,320	3,120	3,420
Capital and other costs (14% of investment)	1,680	1,680	1,680	1,680	1,680
Estimated annual cost	2,600	3,300	4,000	4,800	5,100

Uptown plant, 1,600 megawatts--Cost $16,000,000

	Percent SO_2 Removal				
	20	40	60	80	90
	(hundred thousands)				
Variable costs	1,160	2,160	3,160	4,160	4,560
Capital and other costs (14% of investment)	2,240	2,240	2,240	2,240	2,240
Estimated annual cost	3,400	4,400	5,400	6,400	6,800

been assumed that desulfurization below the one-percent sulfur level is not technically or economically feasible and that desulfurization to levels above 1.5 percent is not economically feasible. Heat content of desulfurized coal has been assumed to remain constant at 24 million BTU per ton.

(c) Natural residual oil (Reference 3)

Figure B.6 shows the range of increment costs for power plant residual oil costs vs. sulfur content for the New England area. It also shows the costs assumed to be valid for the purposes of this report. Heat content has been assumed to be constant at 6.3 million BTU per barrel.

(d) Desulfurized residual oil (Reference 4)

Figure B.7 presents the cost per million BTU of desulfurizing residual oil vs. percent reduction in the sulfur content of residual oil used prior to abatement (2.5 percent sulfur for all consumers). It has been assumed that desulfurization below the 0.5 percent level is not technically feasible and that desulfurization to levels above 2 percent sulfur is not economically feasible. The desulfurized residual oil has been assumed to be in all respects the same as natural oil.

2. Stack Gas Cleaning (Reference 5)

Table B.1 presents the estimated annual costs of stack gas cleaning installations at both the uptown and the downtown power plants. These costs are based on a recent study of stack cleaning processes applicable to an 800-megawatt power plant, and have been

scaled up by factors of 1 1/2 and 2 respectively for the 1,200- and 1,600-megawatt plants. Some distortions are therefore inevitable. Recent information indicates that a portion of the costs in the study referred to above may be somewhat overstated; however, this overstatement is offset by relatively low fuel costs in the study as compared to those prevailing in the model city. No allowance has been made for revenues earned from the sale of sulfur produced as a by-product of this process.

3. High Stack (Reference 6)

An extremely high stack for a power plant may cause an increase in construction costs of as much as $2.00 per kilowatt over the cost of a "normal" low stack. All other things being equal, operating expenses will not be significantly affected by a high stack, while maintenance expenses will be increased somewhat. Table B.2 presents the estimated increased annual costs of a high stack for the uptown power plant, assuming a 50-percent increase in construction costs over those of the low stack. Not included in table B.2 are the additional costs which would be incurred should a low stack be replaced by a high stack. These would include:

(a) cost of removal of low stack, and

(b) loss on removal of low stack (undepreciated book value of low stack)

4. Replacement Power Plant (Reference 7)

Construction cost for a single plant to replace the existing power plants has been estimated at $115 per kilowatt, which includes

TABLE B.2

ESTIMATED INCREASED ANNUAL COSTS OF A HIGH STACK

Plant size	1,600,000 kilowatts
Increased construction cost	$1.00 per kilowatt
Increased construction costs	$1,600,000
Capital and other costs	14%
Annual expense	$ 220,000
Additional maintenance, estimated	10,000
Estimated increased annual costs	$ 230,000

the costs of additional transmission lines and facilities from the new location to appropriate points within the city. Plant size has not been reduced from the 2,800-megawatt capacity of the existing plants, even though this may result in "excess" capacity because of the higher plant factor which exists for a single plant of this size.

Construction costs of the existing plants have been assumed to be $150 and $100 per kilowatt for the Uptown and Downtown plants, respectively, which appear to be representative of plants with characteristics similar to the plants in the city.

Production costs, not including fuel, have been set at about 0.65 mills per kilowatt hour for the new plant, and 0.8 and 2.2 mills for the Uptown and Downtown plants. These appear to be reasonable approximations of costs which are encountered by similar plants.

FIGURE B.1

INCREMENTAL COST OF COAL
TO POWER PLANTS AND INDUSTRIAL CONSUMERS
VS. PERCENT REDUCTION IN SULFUR CONTENT

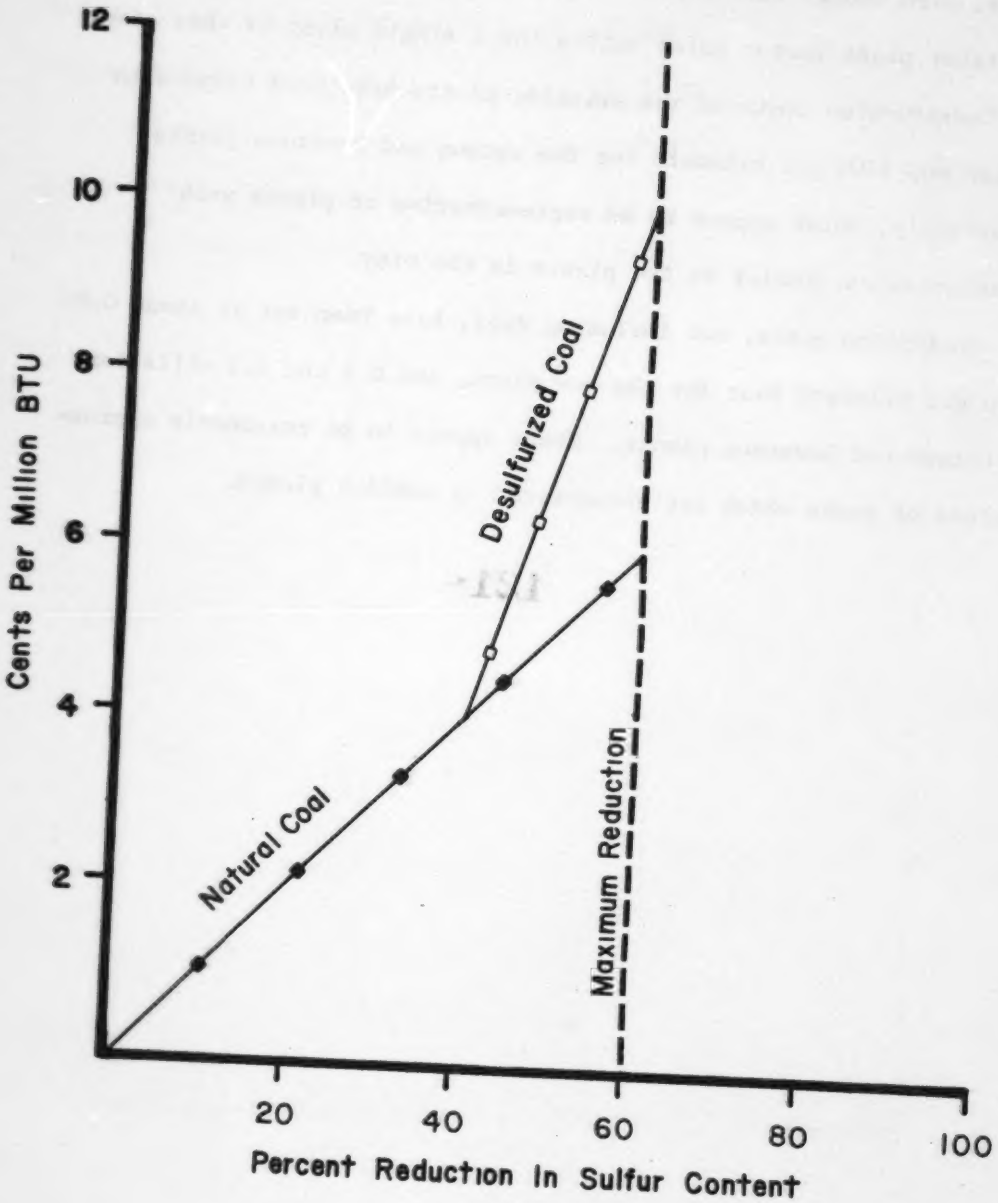


FIGURE B.2

INCREMENTAL COST OF COAL
TO COMMERCIAL AND MULTI-FAMILY CONSUMERS
VS. PERCENT REDUCTION IN SULFUR CONTENT

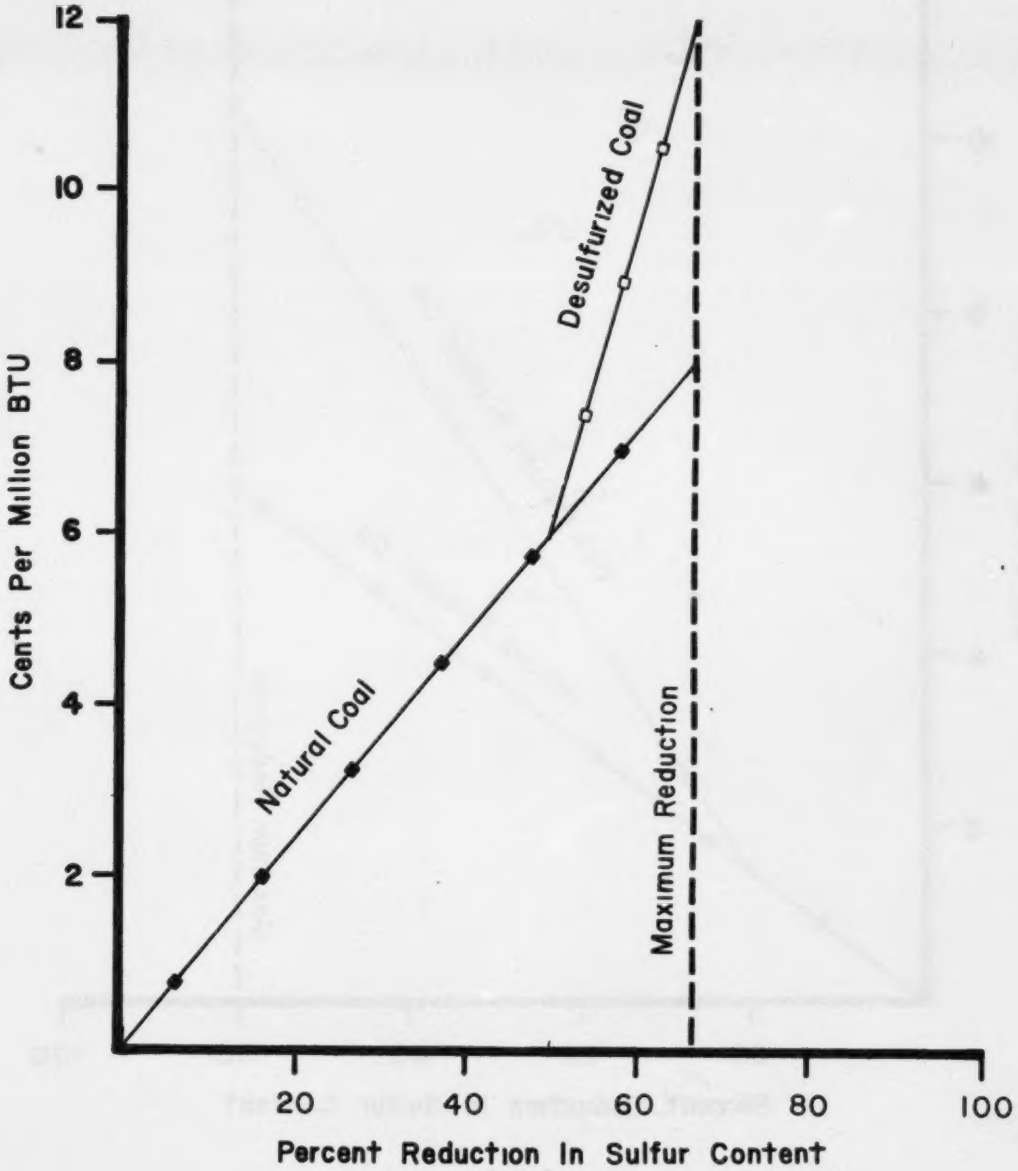


FIGURE 8.3

INCREMENTAL COST OF RESIDUAL OIL TO ALL CONSUMERS VS. PERCENT REDUCTION IN SULFUR CONTENT

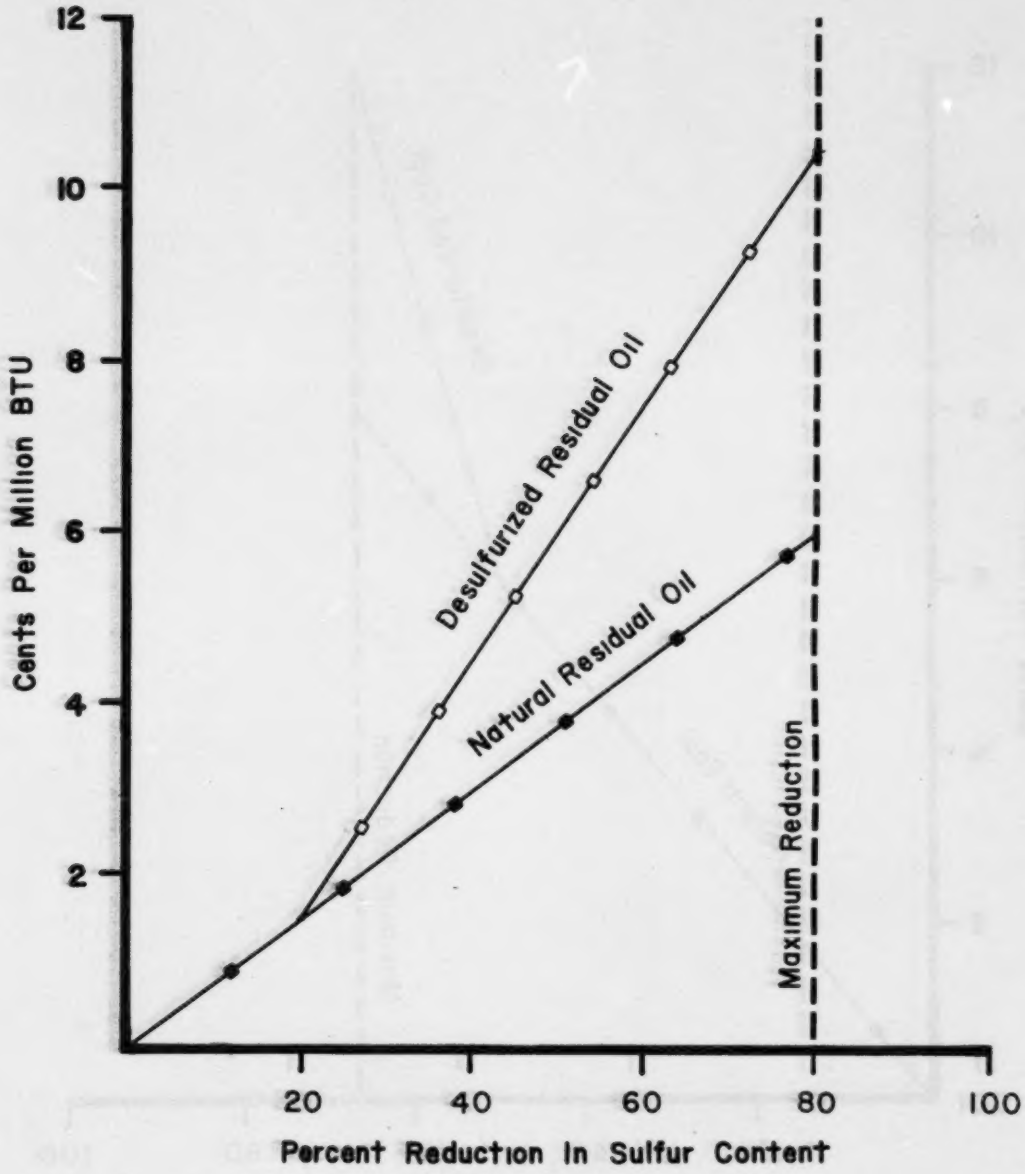


FIGURE B.4

RANGE OF INCREMENTAL COSTS OF
POWER PLANT COAL
VS. SULFUR CONTENT

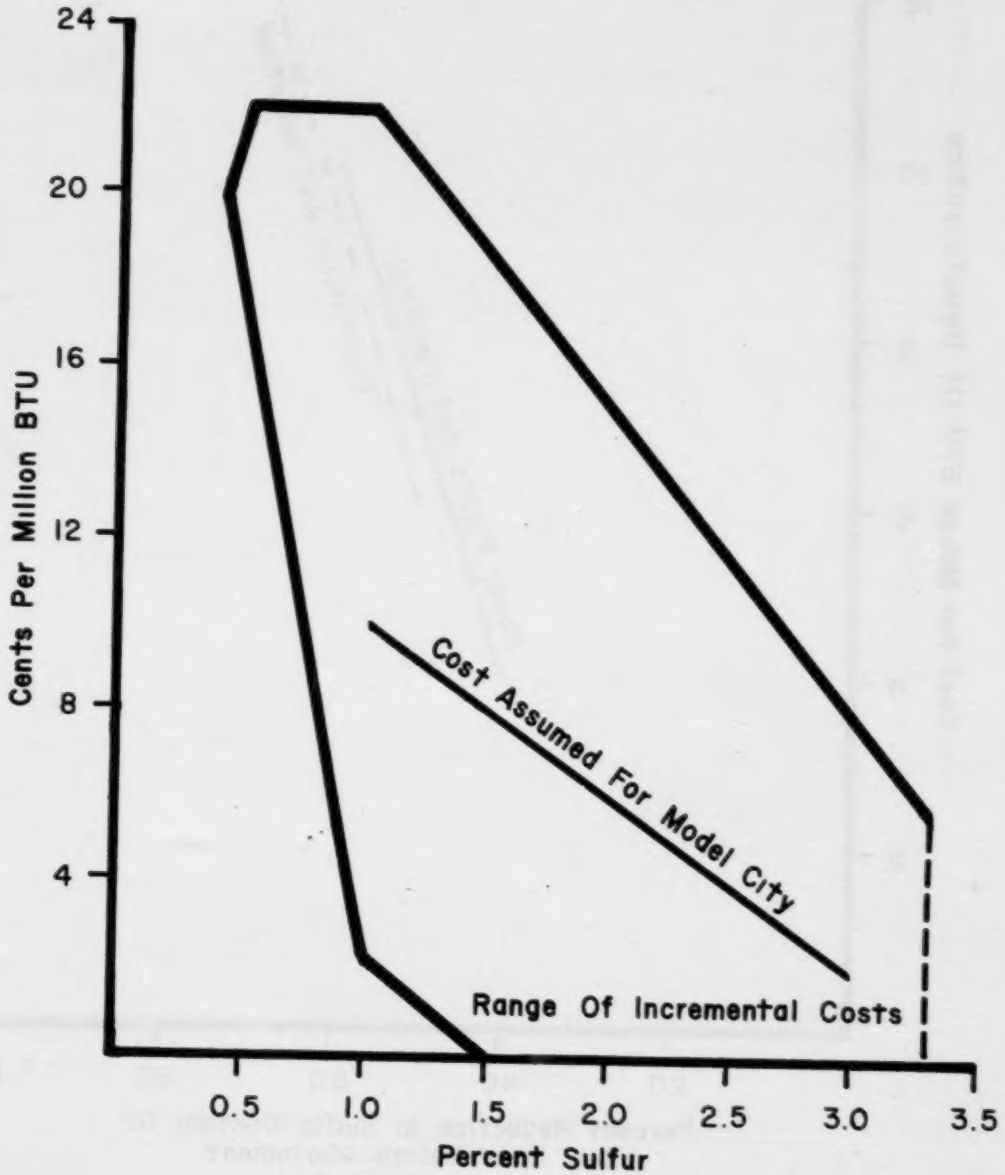


FIGURE B.5

INCREMENTAL COSTS OF DESULFURIZED COAL

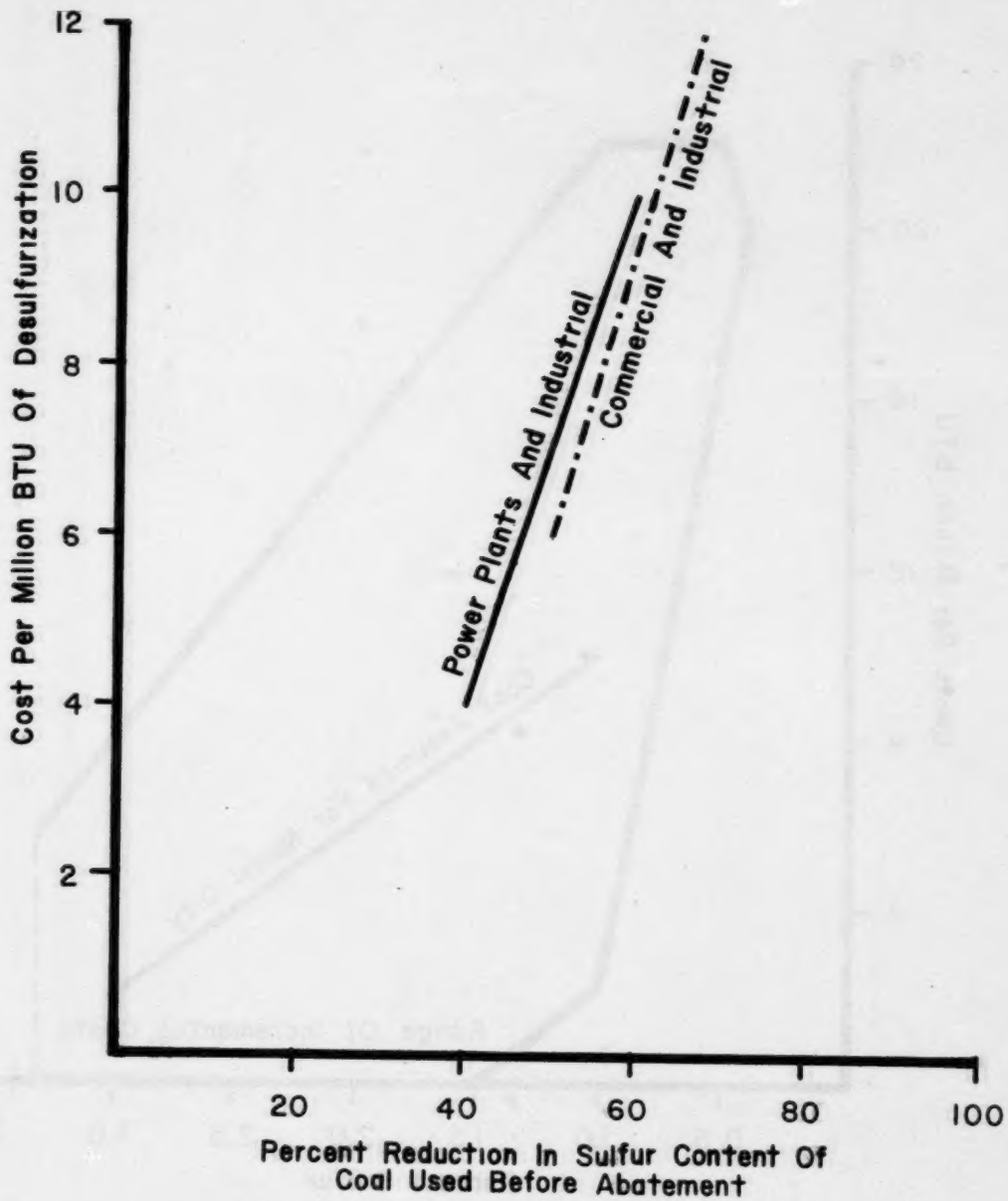


FIGURE B.6

RANGE OF INCREMENTAL COSTS OF
POWER PLANT RESIDUAL OIL
VS. SULFUR CONTENT

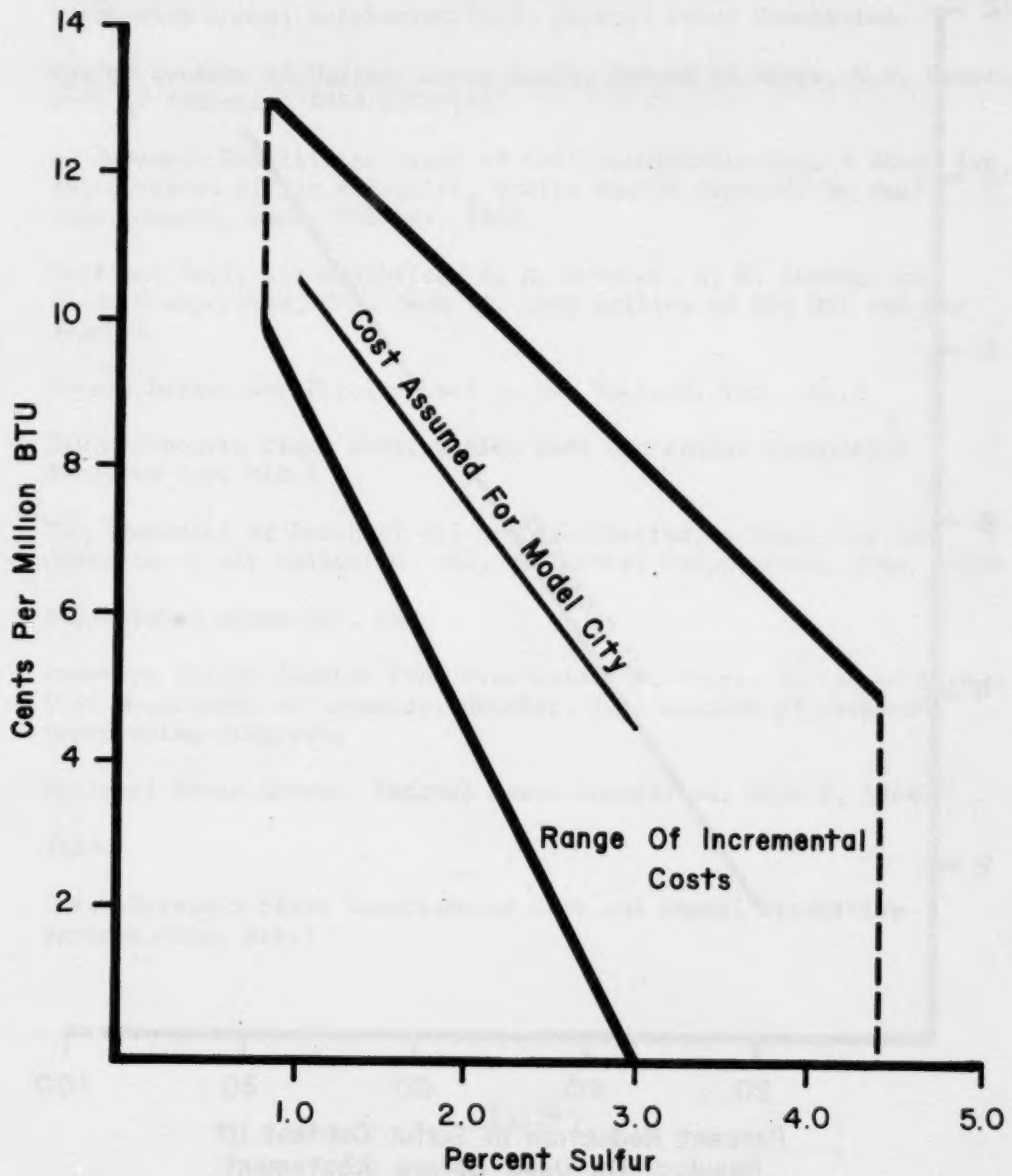
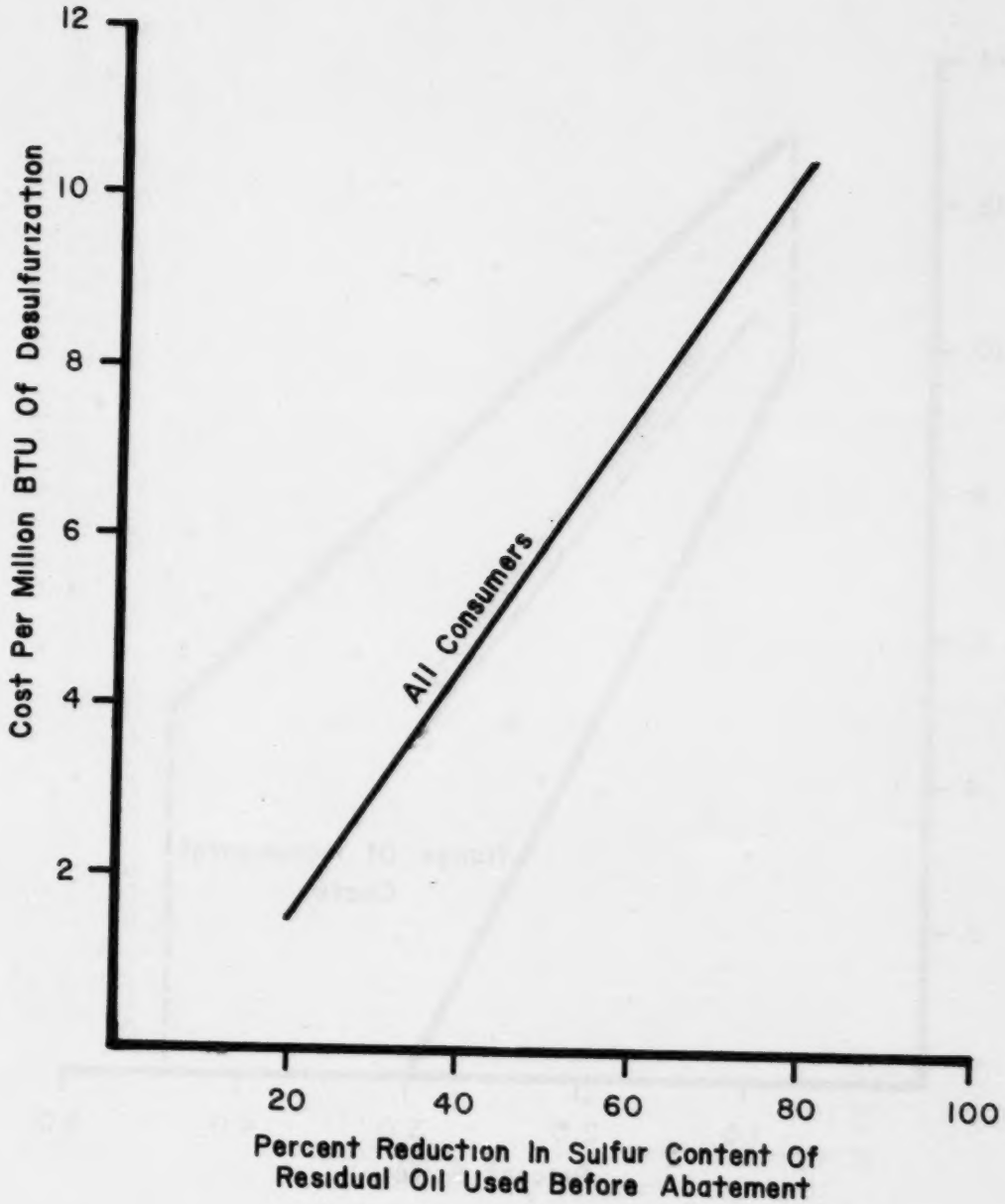


FIGURE B.7

INCREMENTAL COSTS OF DESULFURIZED RESIDUAL OIL



REFERENCES FOR APPENDIX B

1. Unpublished memoranda, F. A. Rohrman, PHS

   Future Market for Utility Cost in New England, Report to the Office of Coal Research, U.S. Department of Interior, by Arthur D. Little, Inc., November, 1966.

   Steam-Electric Plant Construction Cost and Annual Production Expense, Eighteenth Annual Supplement, 1965, Federal Power Commission.

   Sulfur Content of United States Coals, Bureau of Mines, U.S. Department of Interior, 1966 (IC8312)

2. An Economic Feasibility Study of Coal Desulfurization, A Study for the Division of Air Pollution, Public Health Service, by Paul Weir Company, Inc., October, 1965.

3. Residual Fuel, Air Pollution, F. A. Rohrman, J. H. Ludwig, and B. J. Steigerwald, PHS, June 27, 1966 edition of the Oil and Gas Journal.

   Future Market for Utility Coal in New England, (op. cit.)

   Steam-Electric Plant Construction Cost and Annual Production Expenses (op. cit.)

4. The Economics of Residual Oil Desulfurization, A Study for the Division of Air Pollution, PHS, by Bechtel Corporation, June, 1964.

   Unpublished memoranda, PHS

5. Removing Sulfur Dioxide from Flue Gases, S. Katel, Bureau of Mines, U.S. Department of Interior, October, 1966 edition of Chemical Engineering Progress.

6. National Power Survey, Federal Power Commission, Part I, 1964.

7. Ibid.

   Steam-Electric Plant Construction Cost and Annual Production Expense, (op. cit.)

GPO 939-171